Hawaii's Shoreline

APPENDIX 2 - COASTAL CURRENTS
HAWAII INSTITUTE OF GEOPHYSICS

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2/ HAWAII'S SHORELINE
Appendix II

HIG-64-1

COASTAL CURRENTS AND SEWAGE DISPOSAL IN THE HAWAIIAN ISLANDS

By

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FINAL REPORT

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George P. Woollard

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1. INTRODUCTION

1.1 Waste Disposal in Coastal Waters of Hawaii

Throughout the world man has found it expedient to dispose of his domestic and industrial wastes in bodies of water, counting on the water's natural flow for their transportation and dilution, and on the chemical and biological processes in the water for their decomposition. In the Hawaiian Islands, which essentially lack lakes and on which the streams are steep and short, it is of course the ocean on which reliance is made. As shown in Table 1 and Figure 1, wastes of various sorts are discharged at many points into the sea. Disregarding the solid wastes accumulated in sanitary fills behind dikes, sugar-mill wastes and sewage have been the most significant in Hawaii.

Wastes from the sugar plantations were of small importance until mechanical harvesting operations were introduced in the late 1930's. By the late 1940's significant problems had arisen. Trash and mud brought in with the cane and washed off at the mill were being wasted to the sea at many points. The mud caused unsightly discoloration and probably affected significantly the growth of marine organisms, although the extent of such effects is yet undetermined. The trash had a tendency to raft sufficiently to constitute a hazard to navigation, and has undoubtedly contributed to the problem of stagnation in some harbors. In the last decade the problem has abated somewhat with the installation of hydroseparators at the sugar mills. Solids from the separators are trucked or sluiced to land disposal areas, but muddy water is still discharged at many coastal points and trash continues to escape at some.

Table 1.

Municipal and Industrial Waste Disposal in Coastal Waters of Hawaii in 1962

(Modified from Public Health Service, 1963)

Place	Agency	Est. Pop. Served	Type*	Treatment*	Discharge Point
KAUAI					
Kilauea	Kilauea Sugar Co.		sug. mill	none	Ocean
Kapaa	Mahelona Hospital	140	san. sew.	Se	Ocean
Kapaa	Hawn. Fruit Packers Ltd.		pine. can.	Sc	Lagoon to ocean
Lihue	Lihue Plantation Co.		sug. mill	none	Ditch & ocean
Nawiliwili	Kauai Surf Hotel	1,000	san. sew.	Se, Cl	Lagoon to ocean
Koloa	Grove Farm Co.		sug. mill	Sc	Lagoon to ocean
Lawai	Kauai Pineapple Co.		pine. can.	Sc	Ocean
Port Allen	Kauai County	500	san. sew.	none	Ocean
Kekaha	Kekaha Sugar Co.		sug. mill	Sc	Ditch & ocean
OAHU					
Kahuku	Kahuku Plantation Co.		sug. mill	Sc	Lagoons & ocean
Waialua	Waialua Agr. Co.		sug. mill	Se	Ditch & ocean
Kaneohe	Honolulu Div. Sewers	150	san. sew.	Se, Cl	Kaneohe Bay
Kaneohe	Honolulu Div. Sewers	15,000	san. sew.	Se, Cl	Kaneohe Bay
Kailua	U.S.Marine Corps	8,700	san. sew.	Se, Fi, Cl	Ocean
Maunalua	Kaiser-Hawaii Kai	2,600	san. sew.	Se, Cl	Lagoon to Kuapa Pond & ocean
Honolulu	Honolulu Div. Sewers	269,000	san. sew.	none	Ocean
Honolulu	Calif. Packing Corp.		pine. can.	Se, Cl	Kapalama Basin
Honolulu	Hawn. Pine. Co.		pine. can.	Se, Cl	Kapalama Basin
Honolulu	Libby, McNeil & Libby		pine. can.	Sc	Kapalama Basin
Honolulu	Honolulu Airport	?	san. sew.	none	Ocean
Honolulu	Tripler Hospital	?	san. sew.	none	Ocean
Hickam Field	U.S. Air Force	9,000	san.sew.	none	Ocean
Pearl Harbor	U.S. Navy	?	several san. sew.	none	Pearl Harbor

Table 1. (continued)

Place	Agency	Est. Pop. Served	Type*	Treatment*	Discharge Point
Halawa	Honolulu Div. Sewers	4,700	san. sew.	Se, Cl	Pearl Harbor
Aiea	Honolulu Div. Sewers	17,000	san. sew.	Se, Cl	Pearl Harbor
Pearl City	Honolulu Div. Sewers	1,500	san. sew.	Se	Pearl Harbor
Waipahu	Oahu Sugar Co.		sug. mill	Se	Irrigation system & Pearl Harbor
Waipahu	Honolulu Div. Sewers	3,000	san. sew.	Se, Cl	Ditch & Pearl Harbor
Ewa	U.S.Navy (Capehart Hsg)	5,000	san. sew.	Se	Pearl Harbor
Ewa	U.S.N.Air Station, Barbers Pt.	8,779	san. sew.	Se, Cl	Ocean
Barber's Pt.	Standard Oil Co.		oil. ref.	Se	Lagoon to ocean
Waianae	Honolulu Div. Sewers	2,000	san. sew.	Se	Ocean
<u>MAUI</u>					
Lahaina	Maui County	1,000	san. sew.	none	Ocean
Lahaina	Pioneer Mill Co.		sug. mill	Se	Ditch & ocean
Wailuku	Wailuku Sugar Co.		sug. mill	Se	Ditch & ocean
Wailuku	Maui County	7,000	san. sew.	none	Ocean
Kahului	Maui County	4,200	san. sew.	none	Ocean
Kahului	Hawn. Homes Comm.	300	san. sew.	none	Ocean
Paia	Maui County	2,100	san. sew.	none	Ocean
Hana	Hana Ranch Hotel	100	san. Sew.	Se	Ocean
<u>HAWAII</u>					
Halaula	Kohala Sugar Co.		sug. mill	none	Ocean
Halaula	Kohala Sugar Co.	1,000	san. sew.	none	Ocean
Honokaa	Honokaa Sugar Co.		sug. mill	none	Ocean
Honokaa	Honokaa Sugar Co.	550	san. sew.	none	Ocean
Paauhau	Paauhau Sugar Co.		sug. mill	none	Ocean
Paauhau	Paauhau Sugar Co.	550	san. sew.	none	Ocean
Paauilo	Hamakua Mill Co.		sug. mill	none	Ocean
Paauilo	Hamakua Mill Co.	550	san. sew.	none	Ocean
Ookala	Kaiwiki Sugar Co.		sug. mill	none	Ocean
Ookala	Kaiwiki Sugar Co.	400	san. sew.	none	Ocean

Table 1. (continued)

Place	Agency	Est. Pop. Served	Type*	Treatment*	Discharge Point
HAWAII (cont'd)					
Papaaloa	Laupahoehoe Sugar Co.		sug. mill	none	Ocean
Papaaloa	Laupahoehoe Sugar Co.	950	san. sew.	none	Ocean
Hakalau	Hakalau Sugar Co.		sug. mill	none	Ocean
Hakalau	Hakalau Sugar Co.	570	san. sew.	none	Ocean
Pepeekeo	Pepeekeo Sugar Co.		sug. mill	none	Ocean
Pepeekeo	Pepeekeo Sugar Co.	700	san. sew.	none	Ocean
Papaikou	Onomea Sugar Co.		sug. mill	none	Ocean
Papaikou	Onomea Sugar Co.	1,600	san. sew.	none	Ocean
Wainaku	Hilo Sugar Co.		sug. mill	none	Ocean
Wainaku	Hilo Sugar Co.	650	san. sew.	none	Ocean
Hilo	Hilo Sugar Co.	250	san. sew.	none	Ocean
Hilo	Hawaii County	5,100	san. sew.	none	Hilo Bay
Honuapo	Hutchinson Sugar Co.		sug. mill	none	Ocean

* Abbreviations:

oil ref. = oil refinery		Cl = chlorination	
pine. can. = pineapple cannery		Fi = filtration	
san. sew. = sanitary sewer		Sc = screening	
sug. mill = sugar mill		Se = settling	

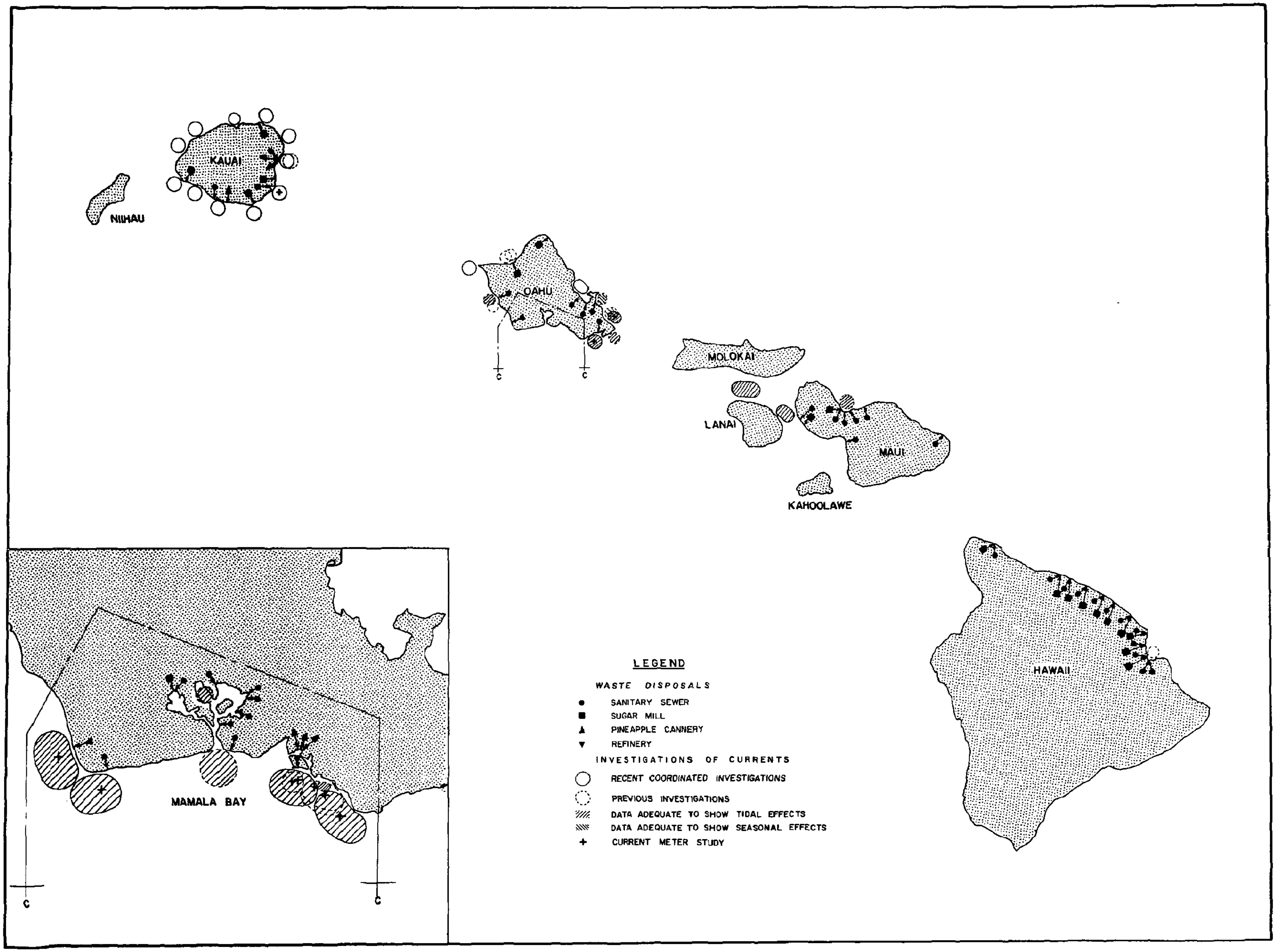


Fig. 1. Index map of the Hawaiian Islands showing points of waste disposal into the sea and areas in which coastal currents have been investigated.

The major waste disposal problems, however, have had to do with sewage. The disposal of most sanitary sewage in Hawaii was originally through cesspools, even in most urban areas. The remarkable permeability of most of the basaltic lavas, of which the islands are predominantly formed, and the permeability of the coral reefs commonly interbedded with other sediments in the coastal plains bordering some of the islands, made such a means of disposal simple and cheap. In some areas, however, cesspools were hardly suitable even with a low concentration of population. With increasing urbanization, and increased density of population in the urban areas, cesspool disposal of sewage has had to give way to sanitary sewer systems that discharge into the ocean. Such systems carry industrial wastes, especially wastes from pineapple canneries, as well as domestic wastes. In most of these systems there are no treatment facilities. The raw sewage is discharged into the sea and the natural currents are relied upon to transport and disperse it.

1.2 Importance of Coastal Currents

Although the high current velocities that are characteristic of continental areas having extreme tidal ranges are not to be found in Hawaii, there still is considerable variation in current velocities from place to place, and also from time to time. Together with the amount and characteristics of the sewage, the currents in the vicinity of a sewer outfall are of critical importance in determining effectiveness in disposing of the waste without detrimental sanitary or esthetic effects. A surface drift moving rapidly toward the shore from a sewer outlet may introduce essentially still undecomposed sewage into a beach area that is otherwise highly desirable for swimming. A current moving seaward may carry the same sewage away from shore and disperse it harmlessly. Thus under some current conditions raw sewage may safely be introduced but, under other conditions, extensive treatment would be required prior to release.

Ideally, what is required is a knowledge of: (a) the initial dilution of the sewage as it is injected into the current moving past the sewer outlet, (b) the time required before the sewage is sufficiently dispersed and decomposed along the path it follows to be considered harmless, and (c) the direction and distance traveled by the sewage in that time. Even if the discharge of the sewage is considered constant at some design maximum value, and the character of the sewage is considered constant also, the variability of the current with time will require knowledge of the frequency of occurrence of current sets of various directions and velocities, including the evaluation of periodic components. Furthermore, the geographic variability of the current requires that the knowledge not be confined to the sewer outlet but that it provide a complete picture of the currents within the distances of concern.

1.3 Previous Studies of Currents in Hawaiian Coastal Waters

Three kinds of previous investigations contribute to the understanding of the coastal currents in Hawaiian coastal waters. The first of these is the study of the general, more or less permanent current systems in the vicinity of the Islands. For many decades such current systems have been estimated by comparing the dead-reckoning positions of ships with navigational fixes. General net surface current charts by month and by one-degree squares are available for the portion of the Pacific in the vicinity of the Hawaiian Islands (Hydrographic Office, 1947, 1950; Brown, ms.). Net current conditions for areas closer to shore, similarly obtained from ship reports, are described in the U. S. Coast Pilot for the Pacific Coast and the Hawaiian Islands (Coast and Geodetic Survey, 1963a).

Only certain very general information, auxiliary to the problems of sewage disposal in coastal waters, can be learned from the older current charts. However, recently, more intensive studies on the ocean currents in the areas around the islands have been made by the Honolulu Biological Laboratory of the U. S. Fish and Wildlife Service, using drift-bottle and drift-card surveys and water-mass analyses (Barkley, ms.). These studies have also been mainly concerned with the general circulation pattern and net flow and, therefore, are applicable only very indirectly to the problems of coastal currents and mixing as they affect the disposal of sewage. However, the information is of use in studies of the possibilities of disposal of solid waste in the sea.

The second kind of investigation consists of local investigations, conducted by engineering firms, of the currents at existing or proposed sewer outfalls. There have been more than twenty such investigations, but the extent of the work reported varies considerably. Some are limited to descriptions of the amount of pollution prior to or following the construction of an outfall. Others report the results of a day, or of a few days, of current measurements using floats or dye. Only two studies lasted as long as a year. In some, the currents were related to wind conditions; in others, to the permanent flow; in a few, the effects of tides were recognized. In conjunction with one there were studies of the dispersion of sewage in the sea and of the rate of bacterial die-off. These local studies are listed in Table 2, and the sites of those which produced significant information on currents are plotted in Figure 1.

Table 2.

Summary of Previous Engineering Investigations of Coastal Currents in Hawaii

Place	Agency	Year	Drift measurements by drogue, drift card dye spot, etc.	Sewage or slick field measurem't*
OAHU				
Kaiaka Bay	BC&A	1962	x	x
Waialua Bay	BC&A	1962	x	x
Kaneohe	HDS	1957		x
Nuupia Pond	H&N, BC&A	1957	x	
Kailua	H&N, BC&A	1959	S	x
Waimanalo	MA	1963	T	
Kalama (Hawaii-Kai)	SLT&H	1962	T	
Ala Moana	A&A, L&W	1960	T	
Kewalo	KT&C	1920	x	
Honolulu	BS	1941		F
Honolulu	M&E	1944		F
Sand Island	HDS	1951	x	
Sand Island	AS&A	1961		x
Pearl City	HDS	1958		x
Pearl City	AS&A	1961	T	
Waipahu	HDS	1957		x
Pearl Harbor Entrance	AS&A	1962	T	
Barber's Point	TAMS	1961	x	
Kaneilio Point	BC&A	1962	x	x
Pokai Bay	SLT&H	1962	T	x
MAUI				
Kahului	H&R	1962	T	x
HAWAII				
Hilo	BC&A	1961	x	x
Kailua-Kona	A&A	1961	x	x

*Abbreviations:

Agencies

A&A HAR Austin & Assoc.
AS&A Austin, Smith, & Assoc.
BC&A Belt, Collins, & Assoc.
BS Bur. of Sanitation, Terr. Poard of Health
HDS Honolulu Division of Sewers
H&N Holmes and Narver
H&R Herschler and Randolph
KT&C Keller, Tay, and Collins
L&W Law and Wilson
MA Marine Advisers
M&E Metcalf and Eddy
SLT&H Sunn, Low, Tom, and Hara
TAMS Tippets, Abbott, McCarthy, Stratton

Drogue, etc. measurements

x = measurements made
T = measurements adequate to determine tidal effects
S = measurements adequate to determine seasonal effects

Sewage or slick field measurements

x = measurements made
F = measurements adequate to define sewage field

The third kind of investigation consists of current meter surveys by the U. S. Coast and Geodetic Survey in the inter-island channels and in other coastal waters. Qualitative results of some of the studies are indicated in the Coast Pilot and quantitative summaries of analyses of two surveys in Auau and Kalohi Channels appear in the Tidal Current Tables of the Coast and Geodetic Survey (1963b). Analyses of most of the surveys are still incomplete, however.

1.4 The Present Studies

The investigation on which this report is principally based was undertaken as one component of the studies involved in the development of a general shoreline plan by the Hawaii State Department of Planning and Economic Development. It was undertaken under contract with that Department, with financing in part through an Urban Planning grant from the Federal Housing and Home Finance Agency. The proposal for the investigation was submitted by the Hawaii Institute of Geophysics in recognition that disposal of sewage from the urban areas of the Hawaiian Islands, in such a manner as to avoid pollution to recreational waters, harm to fisheries, and other damage, is becoming increasingly difficult as the urban areas and the amount of sewage described from them increase. Engineering studies of the most economical sites and means for sewage disposal at sea have been severely limited by inadequate knowledge of the local conditions that affect the released waste, currents, mixing, and decomposition in the sea. These conditions vary greatly from place to place, so that studies must be made locally. In addition, however, basic studies were required, because very few studies have been made of sewage disposal factors in tropical marine waters that provide any fundamental and generally applicable data.

As originally proposed, the general objectives of the study were: (a) to summarize available information applicable to the problems of coastal currents, mixing, and remineralization of sewage in Hawaii and similar areas; (b) to provide answers to the most pressing local problems concerning the marine environment and sewage disposal, e.g., information on current and mixing conditions in specific areas where sewage outfalls are contemplated, or where sewage disposal has been troublesome; (c) to investigate the seasonal changes in oceanographic and meteorological conditions, and to define the "critical conditions" to be considered in planning and designing of the outfalls; (d) to generalize from the interrelated information in such a way as to permit its adaptation to a variety of locations; (e) to prepare plans, procedures, methods, and equipment for such additional local investigations as may be required when new related problems arise.

The study was started in June 1962. The field work was carried out using chartered vessels, especially the 43-foot yawl, "Thunder Bird", as well as the University's 83-foot research vessel, "Neptune I", and to some extent, the 40-foot "Salpa". The field work was concentrated mainly on the island of Oahu for reasons of economy and because the most immediate and serious practical problems of sewage disposal are concentrated on this island. Some field work along the coasts of Kauai has been done, however. The methods and instruments used are briefly described in an appendix to this report, which also contains the actual numerical data collected in the studies.

Office work included the analysis of the field data and plotting of results, the review of previous reports and background literature, and the analysis or re-analysis of some of the data obtained in the previous investigations. A preliminary report on the study (Avery, Cox, and Laevastu, 1963) was submitted in January 1963. The Institute of Geophysics investigation was closely coordinated with one undertaken by the Engineering Experiment Station of the University of Hawaii under contract with the State Department of Health and directed by William Tinniswood. Some of the most important results of the latter investigation are included in this report.

1.5 Scope and Organization of Report

In the investigations reported here, the coastal currents of Hawaii have been more extensively observed by floats and dye than in all previous investigations, and more intensively than in most of the previous investigations. In addition, continuous recording of currents has been carried on at a number of sites for periods ranging from a day to a month. It must be admitted, however, that this more comprehensive work has not produced a clear picture of the current systems which is satisfactory for practical needs. It has indicated, instead, that the systems are much more complex than could have been anticipated on the basis of previous knowledge and, indeed, that many of the simple concepts, on the basis of which sewer outfalls in Hawaii have been designed and even have been built, are inadequate and in some cases are generally erroneous. However, there has emerged from the recent studies a clearer understanding of the components that go to making up the coastal current at any specific place, and the requirements in methods and instrumentation for the adequate study of these components.

In this report the current components are first discussed separately. The actual resultant coastal current systems around each of the islands are then described systematically in as much detail as present information permits, regardless of the source of the information. There follow sections on the practical application of current data, some chemical, biological, and geological aspects of sewage disposal, and the conclusions.

The report is intended for use by persons with some scientific or engineering competence, including planners, sanitary engineers, and coastal engineers, as well as oceanographers. For the most part, descriptions of background oceanographic information that are available in textbooks have been omitted. However, oceanographic factors and processes pertinent to waste disposal in coastal waters that have not received sufficient attention in the past are pointed out and described.

1.6 Acknowledgments

We are particularly indebted to the following: Roger Luther and Donald Cameron, former marine superintendent and captain, respectively, and the crew of the Neptune I, from which much of the field work was done; William Tinniswood of the College of Engineering, who generously allowed the use of data derived in his concurrent study; Richard Barkley and Gunter Seckel of the Honolulu Laboratory, U. S. Bureau of Commercial Fisheries, who discussed at length the present status of knowledge of the permanent flow; Bernard McMorrow and Robert Tam of the Department of Health, who discussed sewage and sanitation problems with us; William Morris of the Department of Planning and Economic Development, who provided liaison with that Department; Ethel McAfee, for editorial assistance; Roy Kaneshiro and Jerry Kusunoki, for plotting the data; and Toshitsugu Sakou of the Institute of Geophysics and the College of Engineering, for assistance and advice in the preparation of this report.

2. COMPONENTS OF COASTAL CURRENTS IN HAWAII

2.1 Components of Coastal Currents in Hawaii

The actual surface current at any time and place is actually the resultant of components having several different driving forces. The oceanic current sweeping past the Islands is the underlying component. Generally, this "permanent flow" sets toward the west, but its direction varies somewhat, especially seasonally, and it also has superimposed upon it large-scale eddies that may cause considerable temporary changes in direction and in strength. Tidal components result from the passage of the astronomical tide waves past the Islands, wind components are set up by the drag of the wind on the surface, and there is also a mass transport associated with the movement of wind waves. The resultant current is of course greatly influenced by the nearshore topography -- at some places the surface current converges, at others it diverges, in still others eddies are formed.

Each of the components is variable in direction and in strength, and for each kind of variability there are characteristic periods. The periods for the tidal currents are well defined, semi-diurnal and diurnal. Variabilities associated with the wind, the waves, and the permanent flow have other periods, including an important annual one. No study of currents can be considered comprehensive unless it includes either continuous observations or observations at intervals close enough to disclose the effects of the shorter period variations, in a continuing program or programs repeated over at least a year to disclose the effects of the longer period variations.

2.2 The Permanent Flow and Its Eddies

A few years ago it was generally assumed that the currents around the Hawaiian Islands were largely the result of the generally westerly flow, the Pacific North Equatorial current in the vicinity of the Islands which represents the clockwise circulation of the North Pacific. This "permanent" flow certainly exists in a statistical sense, but even in the open ocean it has been found to be so variable in direction and strength that generalizations as to its characteristics are very uncertain.

The data derived from ship reports and compiled by the Hydrographic Office (1947, 1950) show the irregularity (Figs. 2 and 3). The direction of set, although predominantly west or west-northwest, varies commonly from west-southwest to north-northwest. Northwest sets are more common within a few hundred miles of the Islands than elsewhere, probably indicating a deflection by the archipelago. The average velocity is a little less than 1/2 knot, but ranges from less than 0.1 knot to more than 1 knot. Monthly charts of the permanent flow at the surface prepared by Brown (ms.) from Hydrographic Office data and from which Figures 2 and 3 have been drawn, indicate a somewhat more northwesterly set, on the average, in winter and spring than in summer and fall.

Drift-bottle studies by the Honolulu Biological Laboratory of the Bureau of Commercial Fisheries (Barkley, ms.) particularly point up the irregularities. Drift bottles released southeast of Oahu in May 1961, for example, were recovered not only on Niihau and Kauai but also on the northeast coasts of Lanai, Molokai, and Oahu. The Bureau of Commercial Fisheries' studies also indicate that the Islands cause eddies in the permanent flow downstream, eddies that are 20 to 50 miles across, revolving at a rate

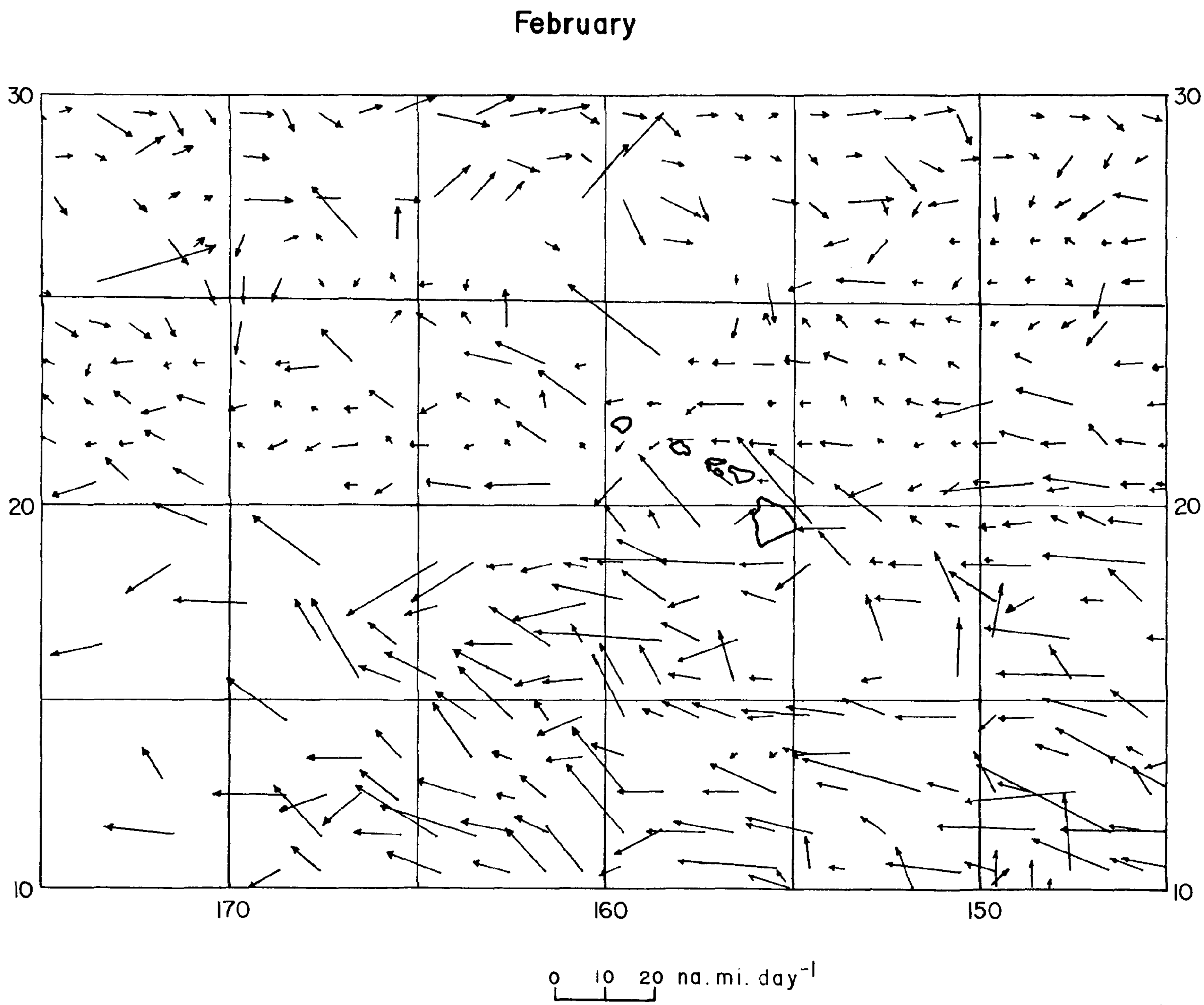


Fig. 2. February surface currents in the vicinity of the Hawaiian Islands indicating the permanent flow pattern as deduced from dead reckoning.

of one turn in 10 days (Anon., 1963). Velocities of nearly 2 knots may be attained near the outer edge of the eddies, five times or more the average velocity of the system.

In the coastal areas of Hawaii the permanent drift has proved surprisingly difficult to disentangle from other current components, largely because of the unexpected prevalence and strength of the reversing tidal components and hence the necessity that the resultant currents be measured over a period of at least a day in order to determine and subtract the tidal effects.

Areas in which the current set is believed to be essentially unidirectional, or in which the net permanent flow has been ascertained by averaging out or analyzing the reversing tidal currents, are as follows (sources of information are discussed in the sections on the current systems around the various islands):

a. The northeast coast of Hawaii from Cape Kumukahi to Leleiwi Point and from Pepeekeo to Upolu Point: Set northwest.

b. Southwest coast of Hawaii from Cape Kumukahi to Keauhou Point: Set southwest.

c. West coast of Hawaii from Kauna Point to Keahole Point: Set generally northwest.

d. Alalakeiki Channel: Net set northwest on northeast side. (A southeast set on the southwest side is also reported, however).

e. South coast of Kahoolawe: Set west.

f. North coast of Maui, Kahului Bay: Set northwest.

g. Kalohi and Auau channels: Net set east about 0.1 knot (?).

h. Southeast coast of Molokai: Net set northeast (?).

i. Southwest coast of Molokai: Net set west.

j. Northeast coast of Oahu from Waimanalo to Kahuku: Set generally northwest.

k. West coast of Oahu, south of Kaena Point: Set northwest (possibly a combination of an eddy at flood and direct tidal current at ebb).

l. South coast of Kauai near Puolo Point: Set west.

m. South coast of Niihau: Set west about 1.5 knots (?).

Most of the directions of set are relatively easy to account for in terms of the set of the permanent flow at sea and its probable deflection close to the island chain. The apparent easterly net drifts in the Kalohi and Auau channels, along the Molokai coast of the Pailolo channel, and along the Kahoolawe coast of the Alalakeiki Channel are not so easily accounted for, but probably represent some form of eddying.

2.3 Tidal Currents

The tides in the vicinity of the Hawaiian Islands are of mixed type, that is, they appear predominantly diurnal at some times and predominantly semi-diurnal at other times, but generally semi-diurnal with a pronounced diurnal inequality. The maximum range is about 3 feet. The tide waves move through the archipelago from the north-northeast toward the south-southwest (Fig. 4). In the open ocean the propagation of these waves must be accompanied by a current setting approximately southwest, more or less in the direction of propagation of the tide wave, at high tide, and a current setting in the opposite direction at low tide.

The nomenclature of tidal currents was developed on continental coasts where the tides form essentially standing waves. On such coasts the

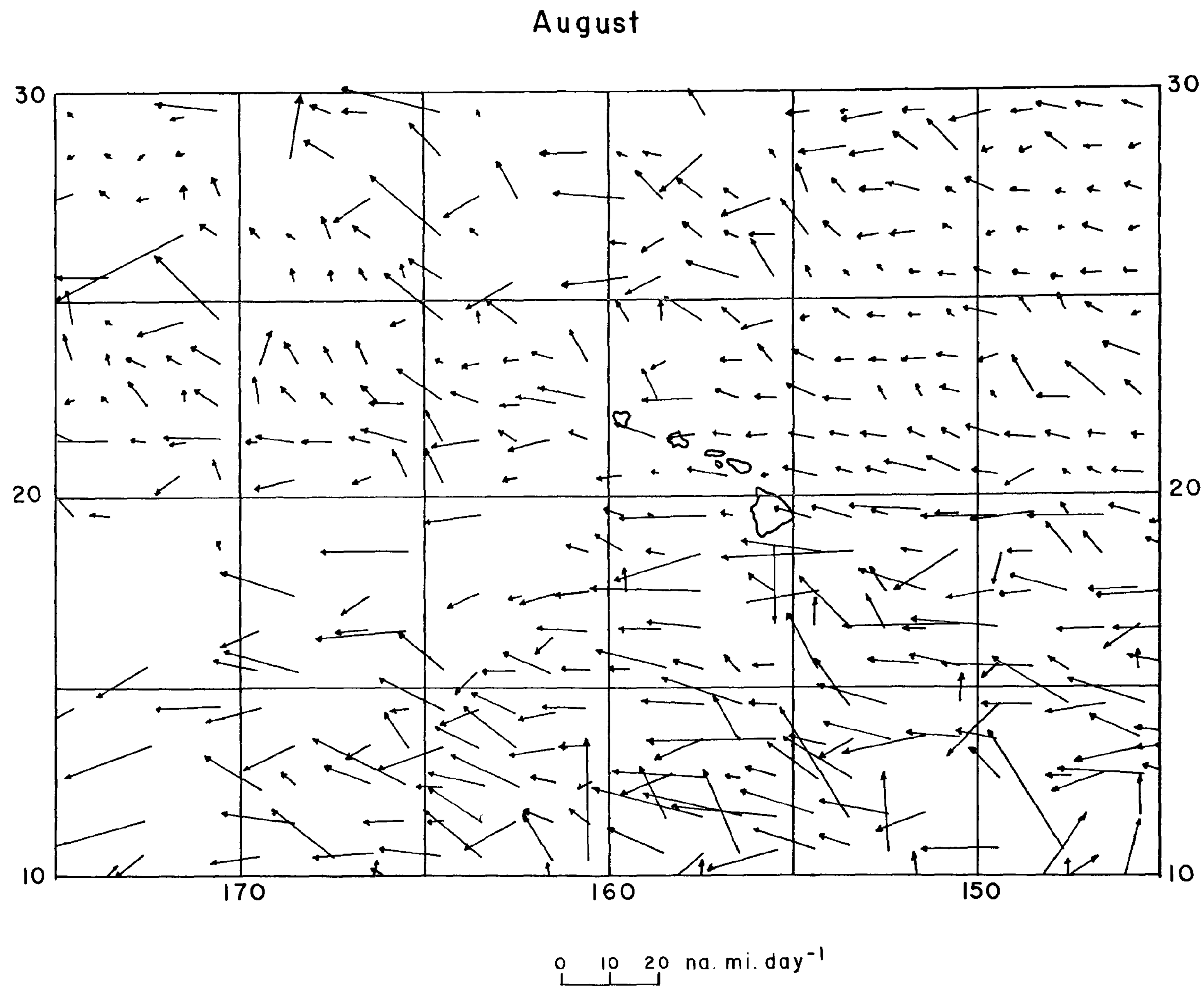


Fig. 3. August surface currents in the vicinity of the Hawaiian Islands indicating the permanent flow pattern as deduced from dead reckoning.

flooding current which carries water landward across the continental shelf and into estuaries is associated with the rising tide, and the ebbing current which carries the water seaward again is associated with the falling tide. In contrast, in the open ocean where the tides form progressive waves, the maximum current velocity in the direction of propagation of the tide wave tends to occur at high tide and the maximum current velocity in the opposite direction tends to occur at low tide. By extension of the original definitions of the tidal currents, the flood current under these conditions is considered to be the current setting in the direction of propagation of the tide wave, and the ebb current, that setting in the opposite direction. In the ocean the actual current directions tend to be rotated clockwise, in the northern hemisphere, from the directions they would have without rotation, so that in offshore waters particles tend to describe ellipses (Fig. 5C) instead of simply oscillating back and forth (Fig. 5A).

The combination of a reciprocating tidal current and a permanent flow creates a resultant current which changes direction, within a certain range of directions, without quite reversing, as shown in Figure 5B. The combination of a rotary tidal current and a permanent flow creates a resultant current which may or may not have a restricted range in directions, depending on the ratio between the minimum velocity of the tidal current and the velocity of the permanent flow, but which has a lower velocity associated with some directions than with others, as shown in Figure 5D.

Considering the smallness of the tide range, the great depth of water surrounding the Islands and the general steepness of their flanks, and the smallness of the Islands in relation to the wave length of the tide, there seemed to be no reason originally for anticipating that the tidal currents would be of much significance in the vicinity of the Hawaiian Islands. Investigations with drogues at Pokai Bay (Sunn, Low, Tom, and Hara, 1962) were the first to indicate that the tidal currents are of consequence. Drogue studies and especially paddle-wheel current-meter studies in the present Institute of Geophysics project, and additional paddle-wheel current-meter studies in the associated Engineering Experiment Station project, also have indicated that tidal currents constitute one of the most important current components, and in some places are the dominant component. Further confirmation has been obtained from Roberts current-meter studies recently published by the Coast and Geodetic Survey (1963b) and from additional, unpublished Roberts meter data. The magnitude of the tidal currents in the coastal waters of Hawaii must be due to the intensification of the currents on the island shelves and in the inter-island channels, but the processes are not yet quantitatively understood.

Further discussion of the tidal currents observed will be deferred to the next section where they can be related to island effects.

2.4 Island Effects

Where the tides move perpendicularly onto an island shelf and toward shore, the phase relations of the tide and the tidal component of the current should expectably resemble those on a continental shelf, that is the maximum current velocities should lead somewhat the maximum and minimum tide levels. A divergence of the flood tidal current component should be expected off the shore of the island facing the direction from which the tide wave approaches (Fig. 5A). From this divergence, currents should sweep around both sides of the island to a convergence on the opposite

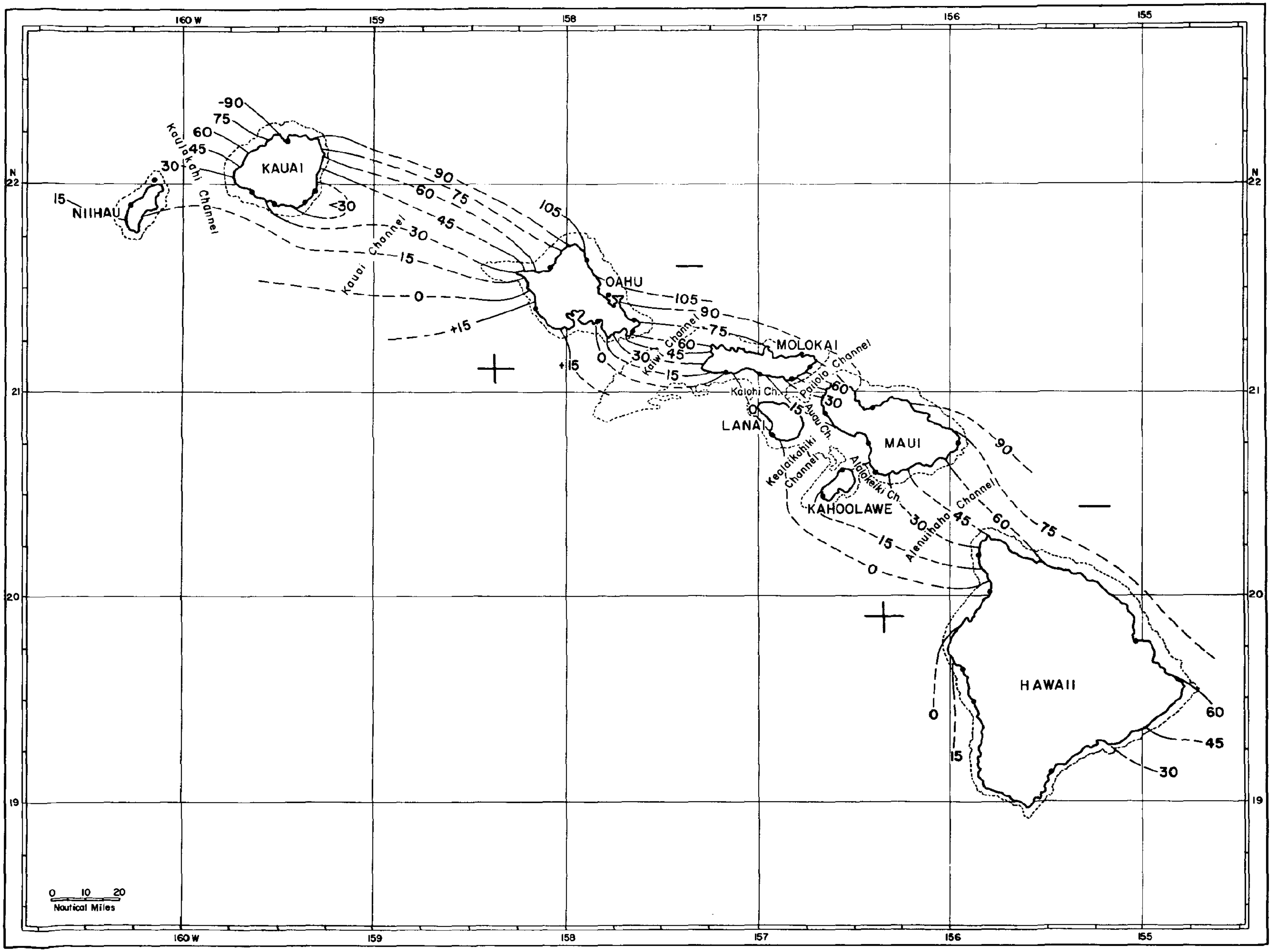


Fig. 4. Co-tidal chart for the Hawaiian Islands.

side of the island. The positions of the convergence and divergence and the directions of set of the currents around the island should approximately reverse with the ebb tide.

The current pattern around a simple circular island resulting from a reciprocating tidal current superimposed on a permanent flow is shown in Figure 5B; that resulting from a rotary tidal current superimposed on a permanent flow is shown in Figure 5C. In both cases it will be noted that:

(a) The flood and ebb convergences and divergences are not on the same axis;

(b) There is a continuous clockwise flow between the flood convergence and the ebb divergence, and a continuous counterclockwise flow between the ebb convergence and the flood divergence; and

(c) In general there are inequalities on most parts of the coastline during the times in which the current sets in the ebbing direction and in the flooding direction.

Considering the complexities of the relationships between tides and currents containing tidal components around even simple islands as discussed above and as shown in Figure 6, it is hardly surprising that the correlation between the tides and the actual currents measured around the Hawaiian Islands should not always be simple. Some additional sources of complexity may also be mentioned. The tidal curves utilized in this study and presented in figures in this report have been based on predictions for Honolulu with standard adjustments for range and time differences at other ports (U. S. Coast and Geodetic Survey, 1962). These standard adjustments took no account of the differences in phase lags and amplitude factors that can be expected between semi-diurnal and diurnal components. Moreover, the sea level changes that actually occur are influenced by unpredicted meteorological factors, such as barometric pressure changes. The ratio between maximum tidal current velocity and tide range for the semi-diurnal tide should be double what it is for the diurnal tide. The ratio between the minimum tidal current velocity and the permanent flow velocity should be double for the semi-diurnal tide what it is for the diurnal tide. None of the Hawaiian islands are circular, and some are quite irregular in shape. The irregularities probably have considerable effect on phase and strength of the tidal currents, and in some areas result in eddies. Nevertheless in spite of the numerous sources of complexity the tidal current picture in some areas has been found through paddle-wheel current-meter studies to be relatively simple.

Near Diamond Head, Oahu, where the current is more regular than at any other place tested, certain things occur rather consistently. In a period of 25 days of continuous observation the current reversed 98 times, without fail, for each change in the stage of the tide, indicating that the current here is mainly controlled by the tide. The ebb current is the strongest and lasts longer than the flood (See Fig. 20, Dec. 4 and 5, 1963). It appears that the maximum ebb current tends to occur at and near low tide in anticipation of a high rise--the higher the rise the stronger the ebb (for the effects of a relatively small tidal change see Fig. 20, Dec. 8 and 9, 1963). The current changes tend to follow a traveling wave pattern. See Figure 19, Nov. 25 and 26, 1963, and others.

Farther west, toward Sand Island, the current pattern becomes less

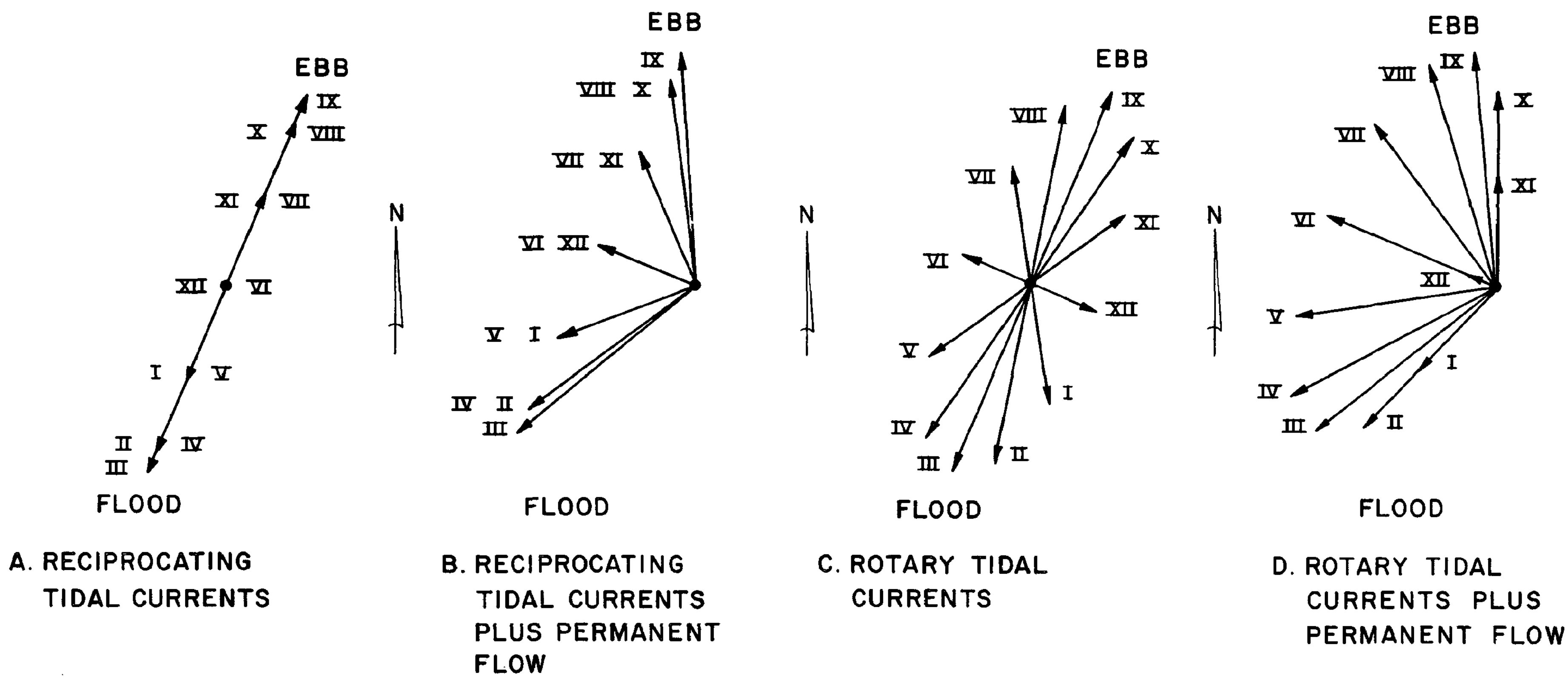


Fig. 5. Diagram showing superposition of tidal current vectors and resultants with permanent flow.
I, II, III, etc. = 12ths of tide period after slack tidal current.

Assumptions: Northern hemisphere

Azimuth of permanent flow set = 292°

$$\frac{\text{Permanent flow velocity}}{\text{Maximum tidal velocity}} = 0.5$$

Azimuth of tide-wave propagation = 202°

$$\frac{\text{Minor axis, tidal ellipse}}{\text{Major axis, tidal ellipse}} = 0.35$$

regular. Figure 21 shows a sample of a 2-week record taken off Magic Island, Ala Moana. As can be seen from data taken on November 11 and 12, 1963, the pattern nearly follows the Diamond Head pattern, but there is a deviation during the early hours of November 12. Figure 21 also includes a sample of data taken off Kewalo Basin in August 1963, which still shows the Diamond Head pattern, but the current appears to be more confused. Figure 22 shows a sample of data taken at the sewer outfall near Sand Island during August, 1963. The Diamond Head pattern is barely recognizable--apparently eddies are causing the difference--although when the tidal range is greater the pattern is more recognizable. East of Diamond Head off Wailupe Peninsula (see Fig. 18) the current pattern is essentially the same as off Diamond Head.

Northwest of Barbers Point the current pattern is again very uniform, as shown in Figure 23, but the tidal current directions are opposite to those at Diamond Head. On the Pearl Harbor side of Barbers Point, however, there is considerable irregularity.

Except for the relative persistence of the ebb current at Diamond Head, these observations fit in well with the concepts diagrammed in Figure 6. Diamond Head is clearly east of the flood convergence and the ebb divergence on the south side of Oahu, and Barbers Point is clearly west of them. The current pattern west of Diamond Head is progressively more confused and the pattern east of Barbers Point is similarly confusing as the areas of convergence and divergence are approached.

2.5 Island and Submarine Topographic Effects

The currents resulting from the combination of the permanent flow and the tidal currents are further complicated by the islands and their submarine topographic irregularities. Upstream of an island (relative to the instantaneous current direction), the approaching current diverges. Downstream, although there is a general reconvergence, the most prominent feature may be a zone of instability and eddying. The convergences and divergences are likely to be intensified at the outer edge of the island shelves where the most abrupt transitions in the tidal currents are likely to occur between offshore elliptical orbits and nearshore oscillatory motions parallel to the coast. The principle of slope convergence formation is illustrated in Figure 7.

Slope convergences have been observed on almost all cruises, and a special study of them was made in the area from Mamala Bay to Barbers Point on April 10-11, 1963, during a period of Kona weather when the winds were very light. The convergences were well demarcated by streaks of calm water and accumulations of seaweed and other flotsam, including sewage. The convergences nearly always occurred over steep bottom slopes, generally at 55 to 75 meters depth. Irregularities and branching were noted. Bathythermograph casts were made on April 10 in the vicinity of one of the convergences. These casts showed a depression of the thermocline where and when a convergence was forming, differing thermal structures on the two sides of the convergence, and mixing with minor inversions in the convergence itself, consistent with the theory of origin illustrated in Figure 7.

The surface divergences which tend to be beneficial in sewage disposal due to their dispersing effects, are not so easily recognized. They seem

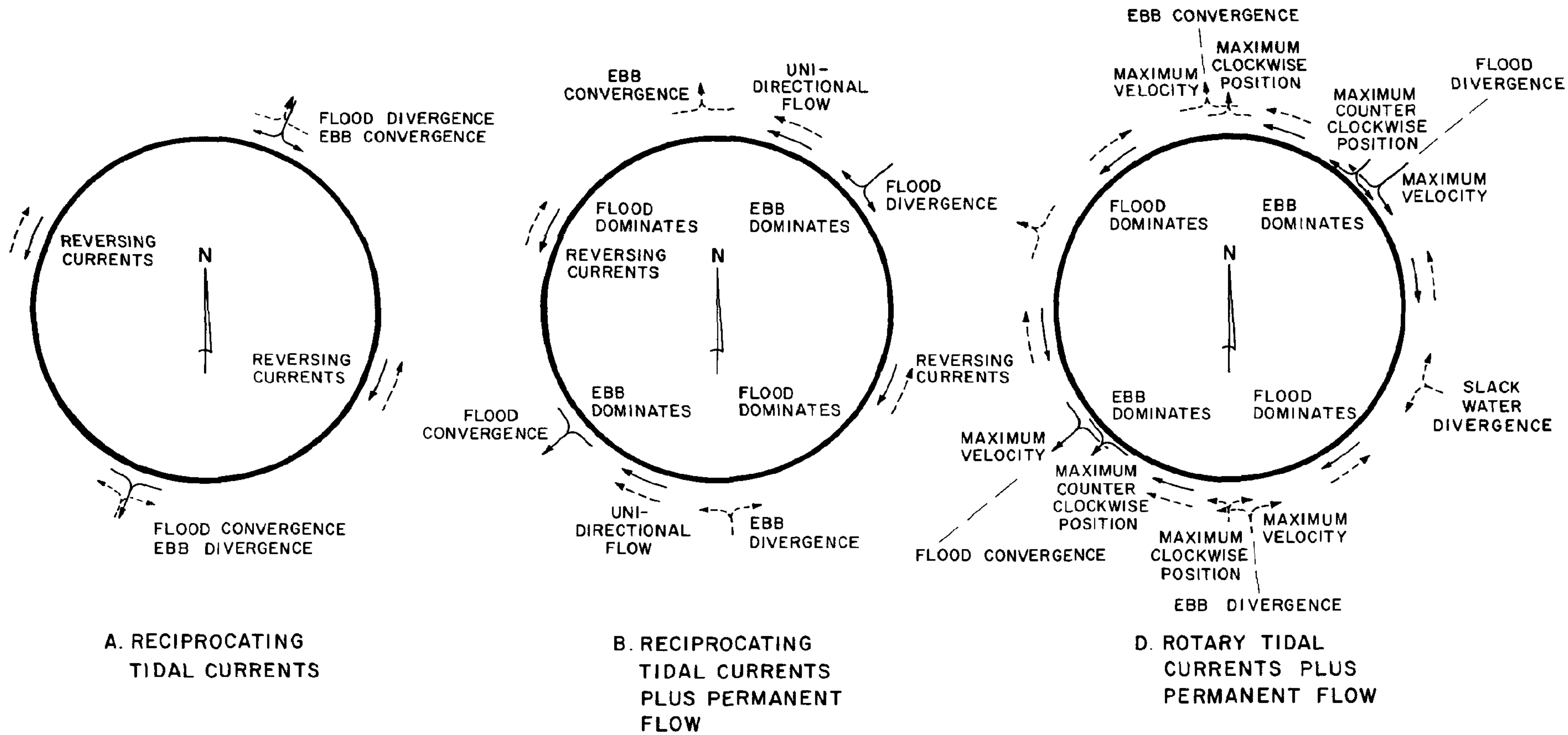


Fig. 6. Diagram showing current patterns around a simple circular island.
I, II, III, etc. = 12ths of tide period after slack tidal current.

Assumptions: Northern hemisphere

Azimuth of permanent flow set = 292°

$$\frac{\text{Permanent flow velocity}}{\text{Maximum tidal velocity}} = 0.5$$

Azimuth of tide-wave propagation = 202°

$$\frac{\text{Minor axis, tidal ellipse}}{\text{Major axis, tidal ellipse}} = 0.35$$

to be distributed over wider areas than the convergences, but they are not accompanied by elevations of the thermocline as distinct as the depressions accompanying the convergences.

It is probable that the sudden appearance of large amounts of "limu" (seaweed) on Hawaiian beaches is sometimes the result of the seaweed accumulating for some time in a convergence, and its concerted movement on shore by wind action when the convergence weakens or breaks down.

La Fond (1962) has related slick streaks, observed close to the continental slope, to convergences associated with internal waves. Occasionally in very calm weather we also have observed several slick streaks, which may be of the sort described by La Fond, in addition to the main zones of convergence on the island slopes.

Earlier studies (Neumann, 1960) have indicated that tidal current ellipses are determined to a great extent by bottom and coastal topography. According to Fleming and Heggarty (1962) and to Lee (personal communication) the currents tend to follow the depth contours, in general, rather than the coastal outline. Some measurements of bottom currents have been carried out on the Oahu shelf and slope using Carruthers' "Pisa" current indicator and current cone. The results showed that the bottom currents tend to follow the depth contours and are approximately the same strength as surface currents or occasionally even stronger along steep slopes.

However, irregularities in coastal topography of the islands are also reflected in irregularities in the depth contours. The irregularities tend to cause eddies and anomalous currents. This is illustrated by the generalized current patterns off Waianae, Oahu, during flood stage, as shown in Figure 36. In the complex eddies shown, which change in tidal rhythm, currents flowing in opposite directions can be found only a small distance apart (see locations A and B).

An interesting eddy formation on the Pearl Harbor side of Barber's Point, Oahu, is shown in Figure 34. The measurements indicate the eddy formation around the headland. Because of the direction of the coast in relation to the direction of ebbing current and the absence of irregularities in bottom topography, no such eddies are formed on the northwest side of Barbers Point, as shown in Figure 35.

Especially strong currents and large eddy formations can be expected where the current sweeps around sharp-pointed headlands, such as Kaena Point, Oahu, near which currents and eddy formations are illustrated for the period of January 3 to 4, 1963 (Fig. 13). It should be noted that the strong current passing around Kaena Point appears not to reverse with the tide. This may be due to the strength of the permanent flow in the area, but it appears likely that it is due in part to the fact that the direction of the flood current eddy along the coast southeast of Kaena Point is the same as that of the ebb current itself along the same coast.

The eddies formed in the lee of islands or local topographic irregularities are likely to persist due to inertia even after they move away from the area of formation.

2.6 Wind-driven Currents and Mass Transport by Waves

The permanent flow described in section 2.2 is largely the result of the drag of wind systems over the ocean. Locally, however, wind drag may not parallel the permanent flow, and the wind-driven current must be treated as a separate component. Independent wind effects are particularly notable upwind and downwind of islands, where the currents may tend, at the very surface, to set respectively onshore and offshore due to wind drag

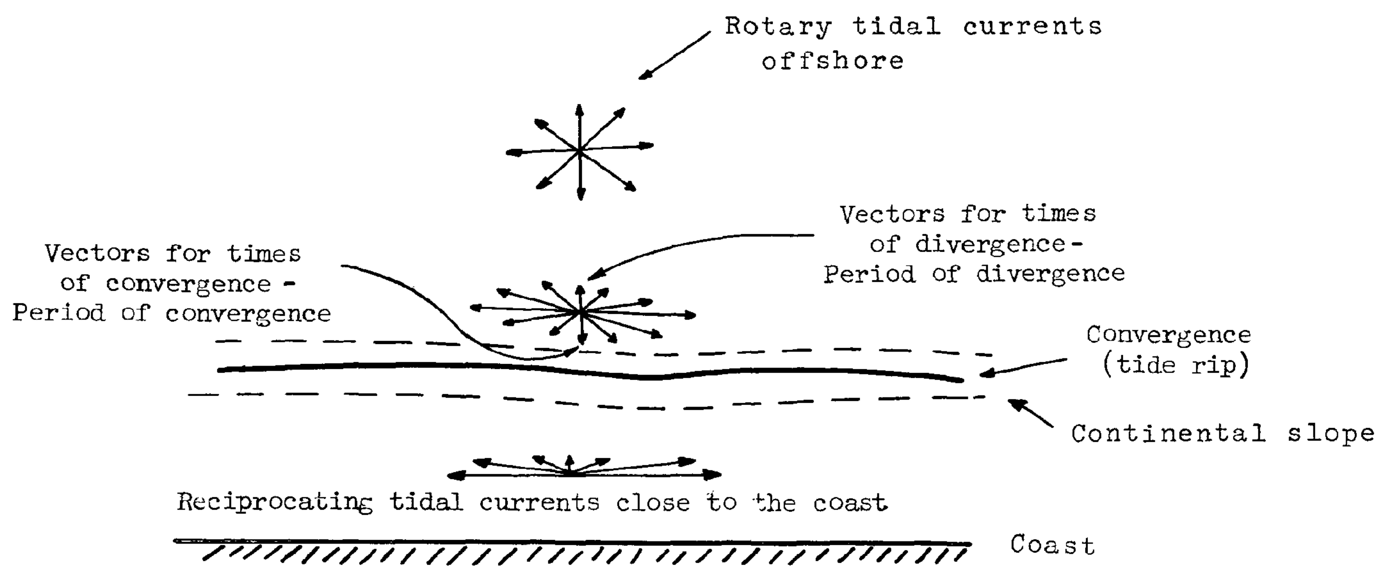


Fig. 7. Diagram showing slope convergences resulting from coupling of coastal reciprocating and offshore rotary tidal currents.

although in depth they may tend to parallel the shore.

The result of the drift of surface water towards the windward coast of an island is a "piling up" of the surface water, referred to as "Anstau". The drift of surface water offshore from the leeward side of an island results in a rise of the deeper water, referred to as "upwelling". A net offshore drift resulting from offshore winds may be seen from drogue measurements at Waianae, Oahu, as shown in Figure 8. Upwelling and anstau effects, on the leeward and windward sides of the island respectively, have also been demonstrated by observations of the depth of the thermocline, as shown by the measurements off Diamond Head given in Figure 6 of the Preliminary Report of this investigation (Avery, Cox, and Laevastu, 1963), and might also be investigated by studies of the distribution of surface temperature.

Differential movement of the water with depth has been studied on windward and leeward sides of the islands in specially-designed experiments with current crosses suspended at different depths. (See Figure 9 in the Preliminary Report, Avery, Cox, and Laevastu, 1963.) The coastward-seaward components at the surface have been found to be compensated usually by opposite components along the bottom (see Figs. 10 and 11 of Preliminary Report).

Several simultaneous observations of the movement of current crosses, drift cards, drift bottles, dye, and wetted paper sheets at the surface show that drift bottles and cards migrate much faster downwind than do the paper sheets at the surface. The movement of dye spots is somewhat slower than the movement of the sheets; and current crosses that have negligible windage lag behind the dye. These observations confirm the conclusions of several earlier investigators that the movement of the drift bottles and drift cards is greatly affected by the wind drag on the portion of the bottle or card that extends above the surface. The comparison of the movement of the wetted paper sheets on the surface with the movement of the current crosses immediately below the surface, leads to the conclusion that the very surface moves faster downwind than does the water layer a few centimeters below it. This observation strengthens the hypothesis of Tomczak (1962), who indicated that there is no discontinuity at the air-water interface with respect to transfer of momentum. Rapid change of current speed with depth causes sheer and turbulence, thus increasing the mixing of any sewage close to the surface.

Besides the drift caused by the wind there is a mass transport of water due to wave motion in the direction of the wave travel. This mass transport by waves has recently been investigated experimentally, as well as theoretically by Masch (1961), who gives appropriate formulae to account for the speed in relation to depth for given wave conditions. As with wind drag, the greatest velocity of mass transport by waves is at the surface. The mass transport and associated mixing by waves are important factors in sewage disposal in coastal waters.

Ordinarily, the mass transport is difficult to separate from the wind drag, but in the lee of an island, where the wind blows offshore, the mass transport may be predominantly alongshore due to the refraction of the waves around the island. Such conditions are encountered off Waikiki. Observations there of the differential current movement with depth plotted in Figure 9 of the Preliminary Report on this investigation showed that the movement of the surface relative to the deeper waters tended to be in the direction of propagation of the swell rather than in the direction

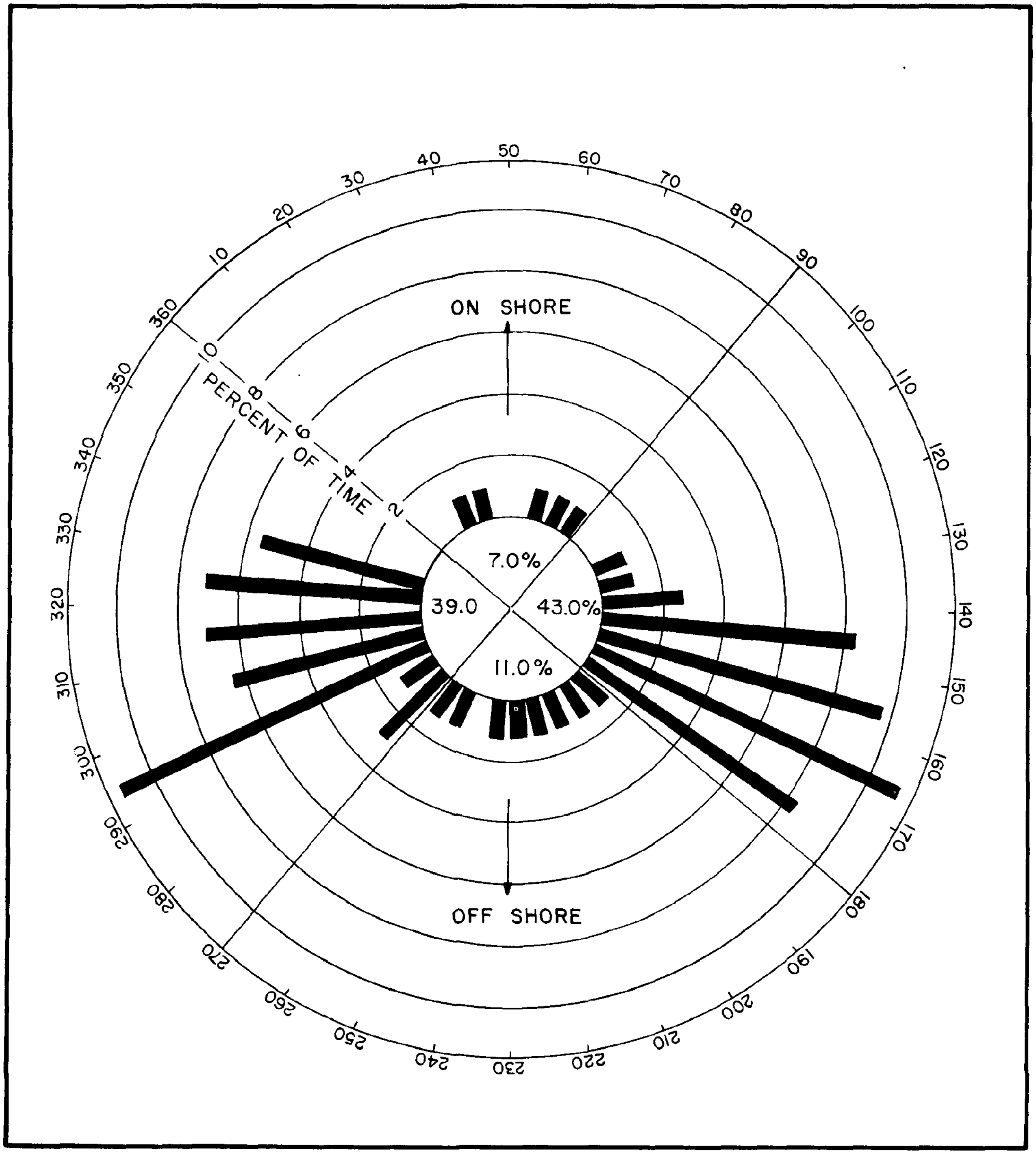


Fig. 8. Directions of drift drogues from two 24-hour cruises off Waianae. (After Sunn, Low, Tom, and Hara, 1962.)

toward which the wind was blowing.

The mass transport becomes accentuated in shallow water. Mass transport of water over a reef, promoted by the breaking of the waves on the reef, is likely to provide the principal circulation inside the lagoon and a pronounced current out through any existing channels.

The outgoing velocities may amount to several knots, depending on the height, period, and direction of approach of the waves, the depth of water over the reef, the width of the reef, and the length of reef from which mass transport is tributary to a channel, although the current in the channels may show some tidal fluctuation in velocity because of the variation of water depth on the reef, there is no reversal. Well-developed examples of reef circulation on two very different scales are those of Kaneohe Bay, Oahu (Fig. 14) and of north Kapaa Reef, Kauai (Fig. 11).

Outgoing currents in reef channels in some localities might be used effectively for sewage disposal, particularly if the sewage release could be regulated in the tidal cycle.

The mass transport associated with waves breaking on a beach causes the alongshore currents that are responsible in large measure for sand transport and for the outgoing rip currents that threaten incompetent swimmers.

3. COASTAL CURRENTS AROUND NIIHAU AND KAUAI

3.1 Niihau

According to the U. S. Coast Pilot for the Pacific Coast and Hawaii (Coast and Geodetic Survey, 1963a) reversing currents have been observed in the Lehua Channel and in the vicinity of Kamalino. Probably the south-setting current in the Lehua Channel and the south-setting current near Kamalino represent flood tidal currents, the opposite sets representing the ebb currents. South of Kawaihoa Point a prevailing westerly current reaching a velocity of 1.5 knots is reported. Little is known about the currents east of Niihau in the Kaulakahi Channel.

3.2 Western Kauai

According to the Coast Pilot (Coast and Geodetic Survey, 1963a): "Current observations taken during a 24-hour period 0.5 mile off Mana Point show a tidal current of 0.2 knot velocity at strength setting southward and northward along the coast. The southward maximum occurs about 3 hours after low water at Honolulu and the northward maximum 3 hours after high water. Similar observations taken near the coast about 3.5 miles southeastward of Nohili Point show a tidal current with velocities generally less than 0.5 knot."

These observations of tidal currents, which fit in with the theoretical concepts discussed in section 2.4, are consistent with drogue measurements made on 23-24 July 1963 (Fig. 9). The measurements show a southeasterly current off Waimea during the change from ebb to flood, a southeasterly current off Kekaha during the flood, no current off Mana during the change from flood to ebb, and northeasterly current off Nohili and Makuaiki Point during the ebb. The maximum current velocities, somewhat over 1 knot, were associated with the ebb current off Nohili. Other velocities were generally considerably less than 1 knot.

3.3 Northern Kauai

Drogue measurements made 24 July north of Haena (Fig. 9) showed a northeast current speed of about 1 knot at the time of a rising tide, but measurements off Hanalei about two hours later during the same tide rise showed a westerly current. Measurements made 25 July off Kilauea and Anahola showed northwest to west currents with speeds as much as 1.8 knots at the time of a high tide. These measurements can be accounted for only by the persistence of the ebb current during the rising tide. The difference in current directions off Haena and off Hanalei may be the result of an eddy or an abrupt reversal from ebb to flood directions or, most probably, the location of the ebb convergence in the region between Haena and Hanalei.

3.4 Eastern Kauai

Drogue measurements on 25 July 1963 showed a north-setting current of 1.8 knots strength at low tide off Anahola and a north-setting current of 0.5 to 1.0 knot off Kapaa about two hours later (Fig. 9). Off Hanamaulu, about the time of the middle of the rising tide, a series of drogues showed a current changing rapidly in both direction and strength. Drogue measurements on 23 July off Nawiliwili showed a southeast-setting current of 1.5 knots strength at high tide. These measurements are all consistent with a flood current setting southward and an ebb current setting northward along this coast.

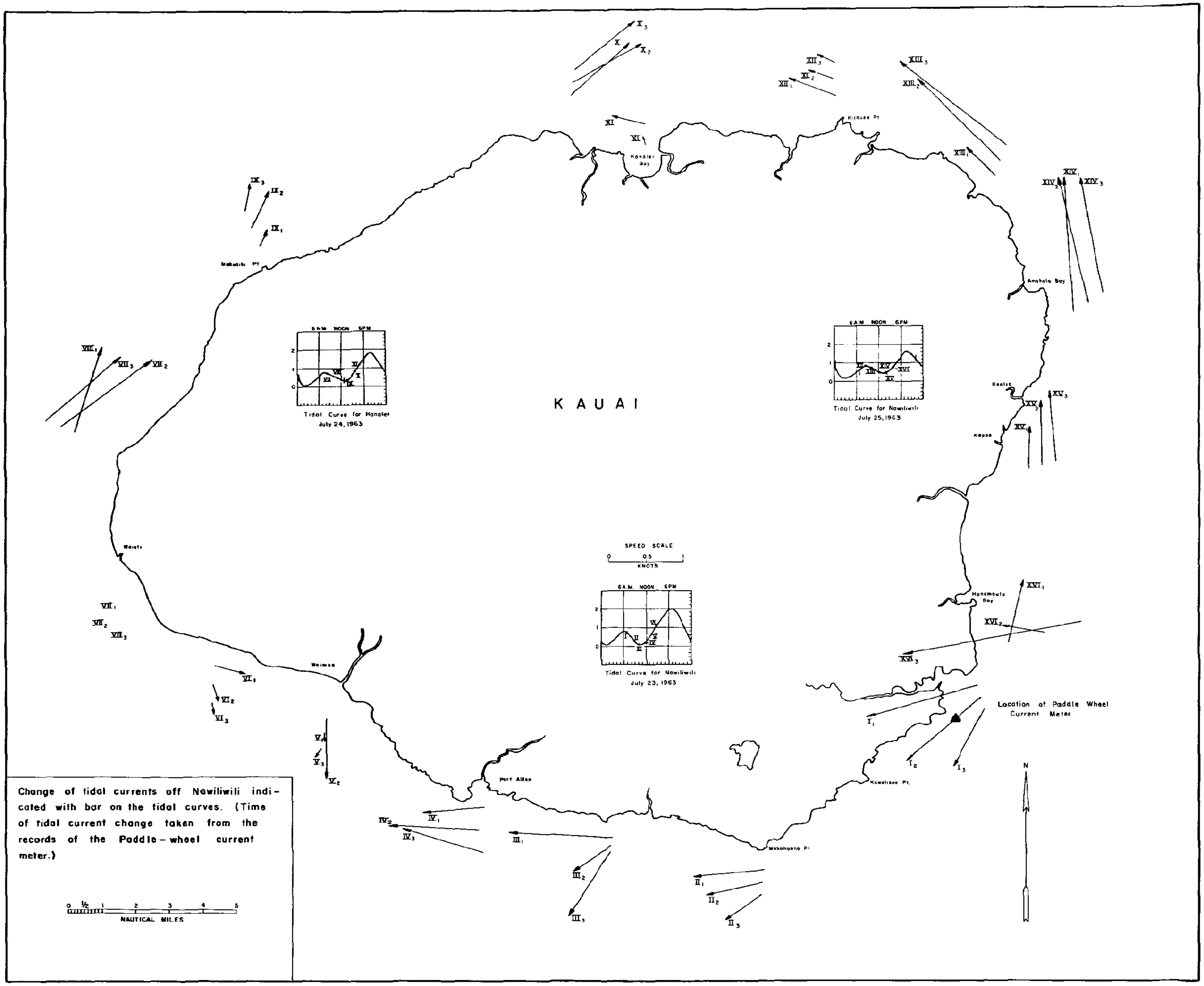


Fig. 9. Results of drogue measurements of currents around Kauai.

Paddle wheel current-meter records for the period 23-25 July 1963 taken at a station a mile south of the entrance of Nawiliwili Bay (Fig. 10) show currents reversing apparently as the result of, but not easily correlated with, tidal changes. The flood flows dominate and the phase relations are difficult to account for. Since the drogue measurements in the area agree with the theoretical pattern mentioned above, it is probable that the meter was in an area affected by eddies.

A study of the currents on the north Kapaa reef by Helfrich and Kohn (1955) showed a typical reef-lagoon circulation (Fig. 11). The water was introduced over the reef edge by mass transport and flowed continuously southward on the reef, regardless of wind and tide conditions, escaping back to the ocean again in a deep-water inlet. Interestingly, Inman, Gayman, and Cox (1963) found that in spite of the strength of the southerly current the sand was transported westward across the reef by the oscillatory currents associated with the waves and under the guiding influence of small channels on the reef surface.

3.5 Southern Kauai

Drogue measurements on 23 July 1963 (Fig. 9) showed west-setting currents averaging about 1 knot from off Makahuena Point to off Port Allen during a time when the tide was approaching low, was low, and beginning to rise. This direction is consistent with an ebb tide only if this part of the coast lies between the flood convergence to the west and the ebb divergence to the east, as discussed in section 2.4.

3.6 Summary of Coastal Currents Around Niihau and Kauai

The comparatively regular shape of the island of Kauai led to the hope that the coastal currents around it would be more regular than those around the other islands.

The drogue measurements made around Kauai are consistent with a current pattern with both tidal and permanent flow components in which the flood current impinges on the island and diverges somewhere west of Hanalei and possibly even as far southwest as Hanamaulu and converges again in the vicinity of Waimea, and in which the ebb current impinges on the island and diverges in the vicinity of or west of Makahuena, possibly even as far northwest as Nawiliwili, and converges again in the vicinity of Haena. The measurements are, however, insufficient to demonstrate the current pattern with certainty.

Current-meter measurements off Nawiliwili support the belief that the currents are controlled in part by the tides, but indicate that their correlation with the tides is not simple.

The current reports from Niihau are consistent with a combination of tidal and permanent flow components in which the resultant flood convergence and ebb divergence are at the northeast point of the island, and in which the ebb divergence is east of Kawaihoa Point and the flood convergence northwest of the Point.

The currents around Niihau and Kauai are shown in simplified diagrammatic form in Figure 39.

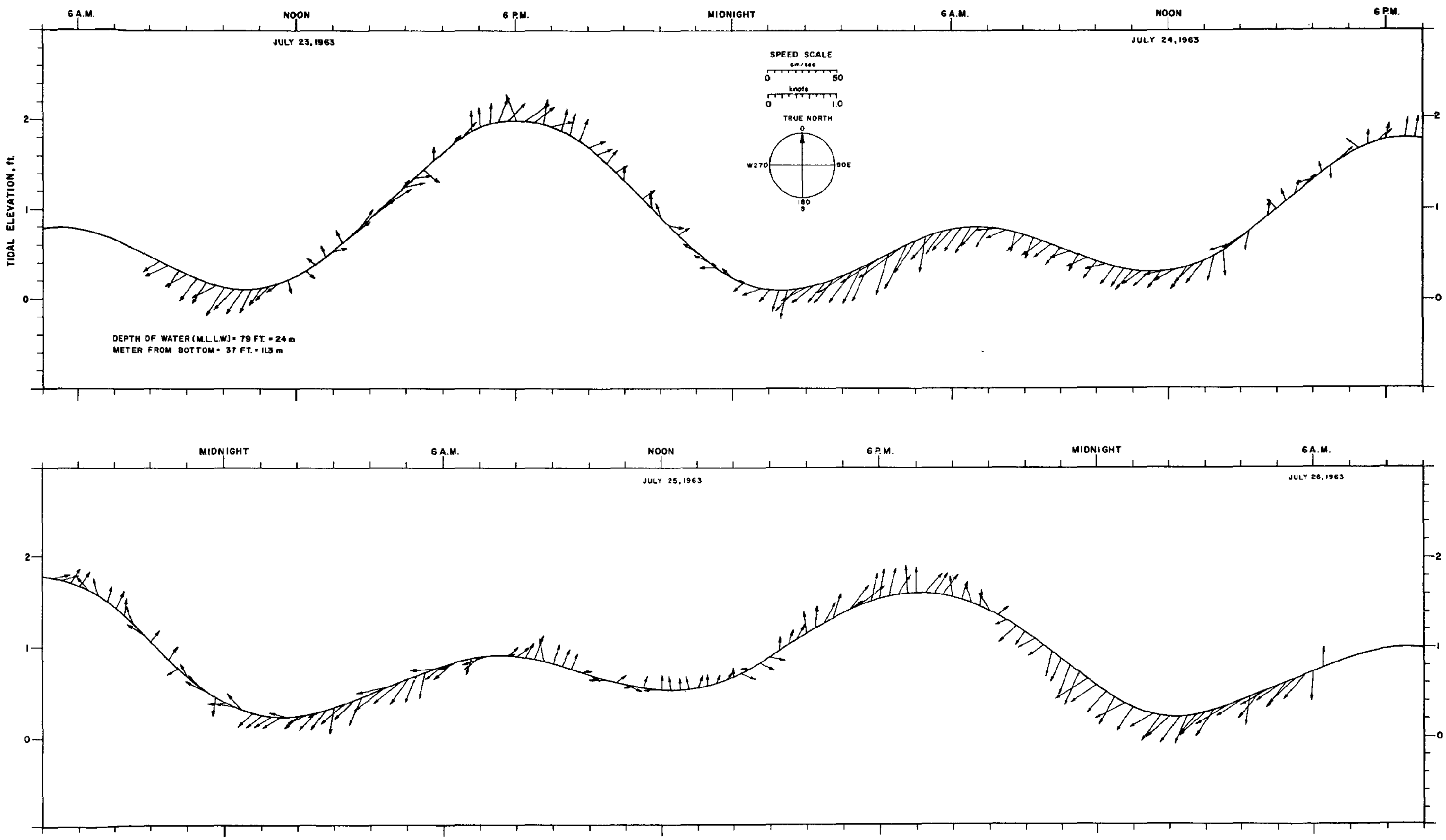


Fig. 10. Paddle-wheel current-meter measurements from southeast of Nawiliwili, Kauai, (top) July 23-24, (bottom) July 25, 1963.

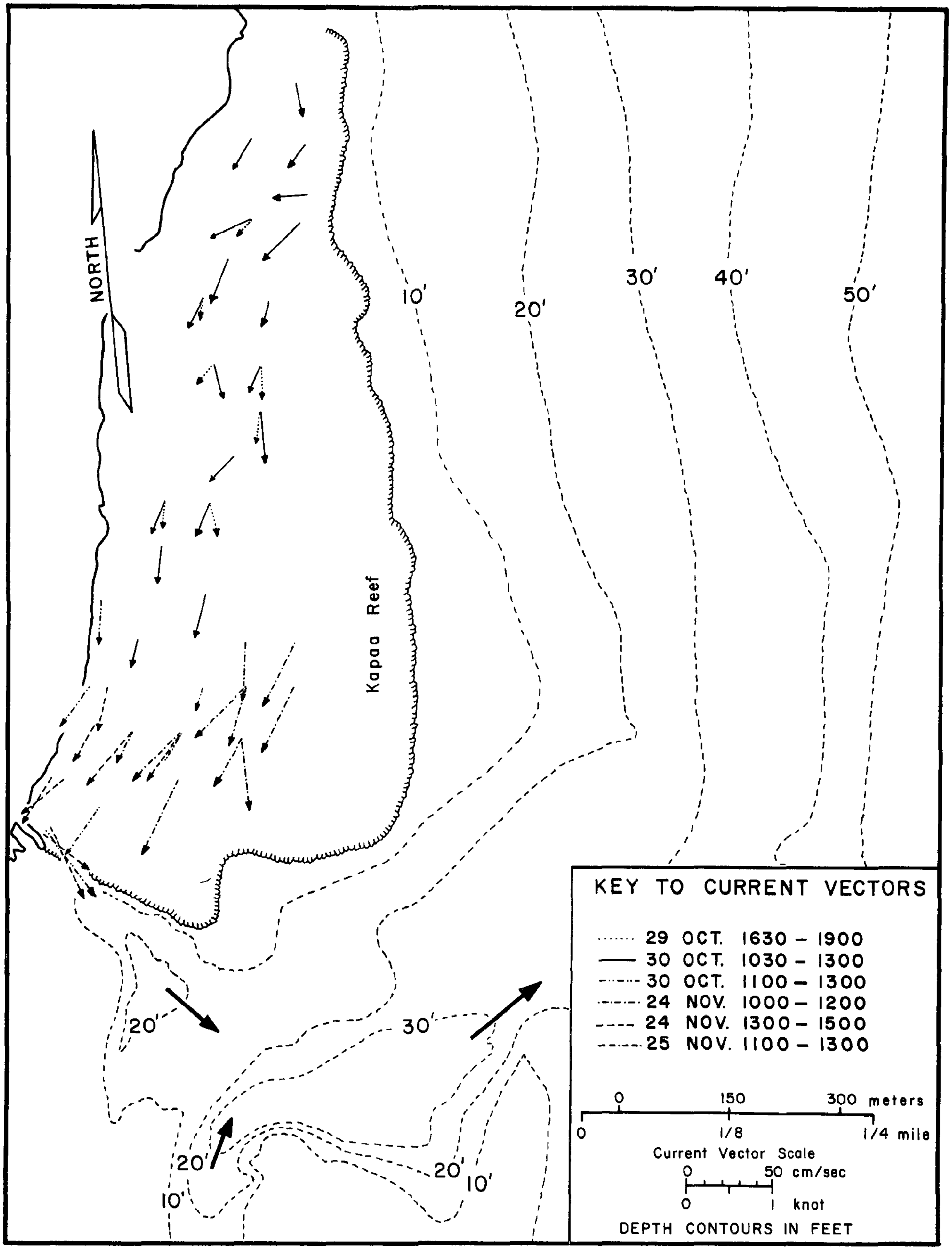


Fig. 11. Currents on the Kapaa Reef (after Helfrich and Kohn, 1955, and Inman, Gayman, and Cox, 1963).

4. COASTAL CURRENTS AROUND OAHU

Because of the number of separate drogue studies and current-meter studies made during the present investigation around Oahu, an index map showing the sites of these studies is included (Fig. 12). The sites of additional studies made in the course of engineering investigations are shown in Figure 1.

4.1 Northwest Coast

Off Kaena Point, as reported by the Coast Pilot (Coast and Geodetic Survey, 1963a) and as observed in the present investigations, there is a generally continuous northwestward current. Coast and Geodetic Survey observations with a Roberts current meter over a 24-hour period showed the northwest current, 0.8 mile south of the Kaena Point light house, to have an average velocity of 0.8 knot and a maximum velocity of 1 knot. Drogue measurements in the present investigation made on 3-4 January 1963 (Fig. 13) showed a west or west-northwest current, of 1 or 2 knots speed, west of the point except at low tide when the current turned north-northwest and over one trajectory increased to 5 knots speed. At all tide stages the current west of the point was fed by convergent currents following both the north and south coasts of the Waianae Range. However, at high tide there was a divergence of about two miles southeast of Kaena Point so that at 4 miles southeast a southeast-setting current suggested the existence of a counter-clockwise eddy south of the point during the flood. A north-northwest set north of the point at low tide, together with eastward sets farther east at Waialua, similarly suggests the existence of a clockwise eddy north of the point during the ebb.

From Kaena Point to Kahuku Point the only current studies which have been made are those of Belt, Collins, and Associates (1962a, c) in Kaiaka Bay, in Waialua Bay, and immediately offshore. In these studies, performed during two days in October and December 1961, the currents were observed by surface floats of various sorts, subsurface drogues, and dye. The results of the studies indicate that the floats and drogues were greatly affected directly by the wind. The records of the dye trajectories are very useful, however, in indicating current sets both in and outside the bays. Both in Waialua Bay inside the breakwater and in Kaiaka Bay the current apparently sets continuously seaward, no doubt as a result of the fresh-water streams entering the heads of the bays. Velocities are about 0.1 to 0.3 knot. Outside Kaiaka Bay the only measurements were on a rising tide, when the current set southwestward with a velocity of 0.1 knot. This set agrees with that measured on a rising tide and at high tide outside Waialua Bay, where the velocities ranged from 0.2 to 0.3 knot. However, at low tide the current was found to set northward with a velocity of 0.1 to 0.2 knot from Waialua Bay.

The currents in Kaiaka Bay are insufficient to prevent stagnation, as indicated by low oxygen content and high biological oxygen demand, and both bays are contaminated bacteriologically.

The reversing tidal currents off Waialua Bay are probably typical of much of the northwest coast of Oahu.

4.2 Northeast Coast-Kahuku to Ulupau Head

According to the Coast Pilot, the "currents off Kahuku Point set westward or northwestward but are sometimes negligible; tide rips have been reported a mile eastward of the point." Assuming that the tide rips occur

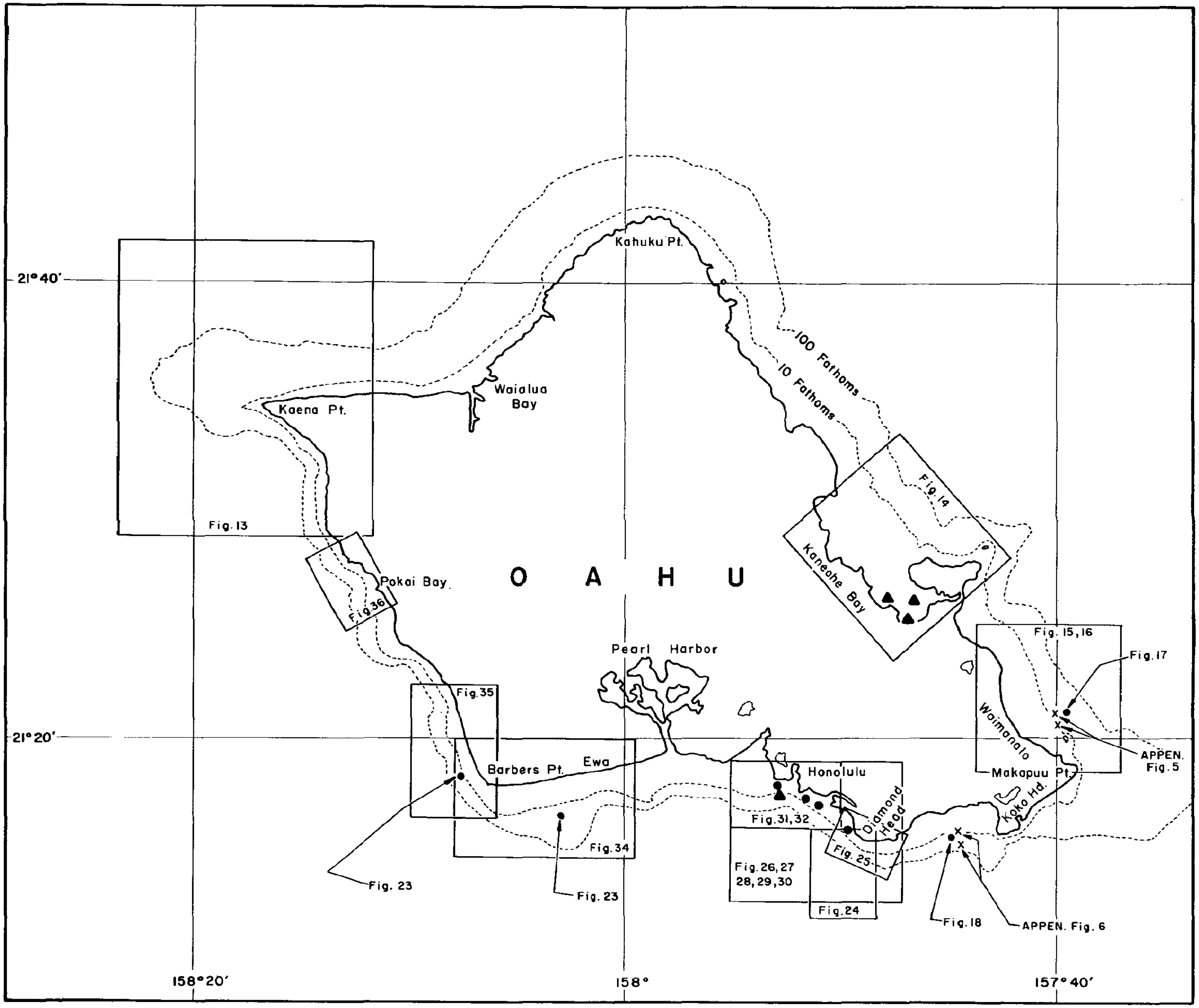


Fig. 12. Index map to figures showing coastal currents around Oahu. Locations of paddle-wheel current-meter measurements are shown by solid circles; Ekman current-meter measurements, by crosses; and locations of chemical studies, by triangles.

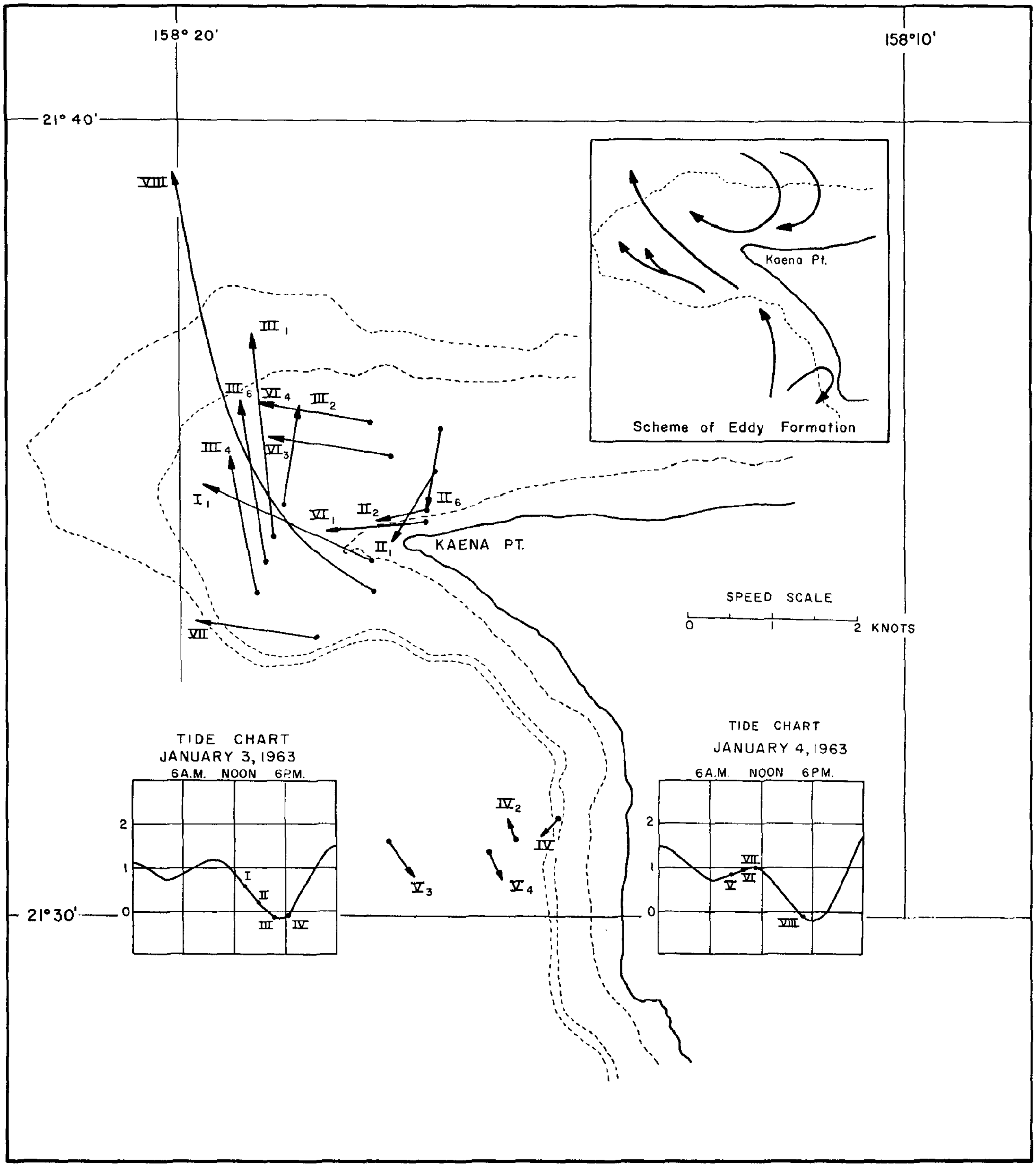


Fig. 13. Results of measurements of currents near Kaena Point, Oahu, on January 3-4, 1963. (Measurements made during predominantly ebbing tides.)

at times when the current parallel to the shore is slight, observations are consistent with the concept that the ebb-stage current convergence is located in the vicinity of Kahuku Point and flood-stage current divergence is located somewhere to the southeast.

The Coast Pilot also indicates that "an eastward current is reported in the vicinity of Mokumanu Islands," near Ulupau Head. Judging from the current measurements in the vicinity of Kailua, described in section 4.4, it is unlikely that there is a continuous eastward current at this place. The report is probably meant to call attention to an occasional exception to the general westward or northward flow described as passing the island. If so the flood-stage current convergence occurs, at least sometimes, off or northwest of Ulupau Head.

Unfortunately there have been no really reliable current measurements made offshore along the coast between Kahuku Point and Ulupau Head.

4.3 Kaneohe Bay

Measurments of the circulation in Kaneohe Bay (Fig. 14) indicate a well developed reef and lagoon circulation of the sort discussed in section 4.5. Water is introduced into the bay by mass transport over the reef and even through the shallow east channel. The surface circulation within the bay is apparently wind driven, and the flow along the bottom is controlled by the configuration of the channels and reefs. Discharge from the bay occurs through the deeper west channel.

The measurements available indicate no tidal reversal in either channel, although it is conceivable that, during periods of calm when mass transport is minimized, there might be an outflow with the ebbing tide through the east channel and an inflow with the flooding tide through the west channel.

Some additional current measurements and analyses of water quality made by students in connection with studies of the distribution of zooplankton (Twesukdi Piyakarnchana, oral communication) indicate that the southeast section of Kaneohe Bay, especially, is rather effectively isolated from the ocean. Although there is separate circulation within the southeast section resulting mainly from wind drag, which maintains aeration even at depth, there is little exchange with the rest of the bay.

A study of Nuupia Pond, a shallow walled-off arm of the bay (Holmes and Narver and Belt, Collins, and Associates, 1959b) showed the currents in the pond to be wind-driven.

A sampling program by the Division of Sewers (1957a) showed low bacterial concentrations except close to shore.

4.4 Kailua

Mention was made of the parallelism of current sets off Kailua to the shore in a Holmes and Narver report of 1957, but the most extensive current observations in the vicinity of Kailua are those of Holmes and Narver and Belt, Collins, and Associates in 1959. Five daytime surveys were made off the base of Mokapu peninsula, one each in January, May, June, July, and August. The currents were observed with surface floats, subsurface floats, and dye. The results indicate that the floats, especially the subsurface ones, were greatly affected by direct wind drag. The dye patch trajectories, not affected by wind drag, indicated that the current set north during rising tide stages, west during a falling tide stage, and northwest at low tide. Velocities are not directly indicated but seem to have been on the order of 0.1 knot.

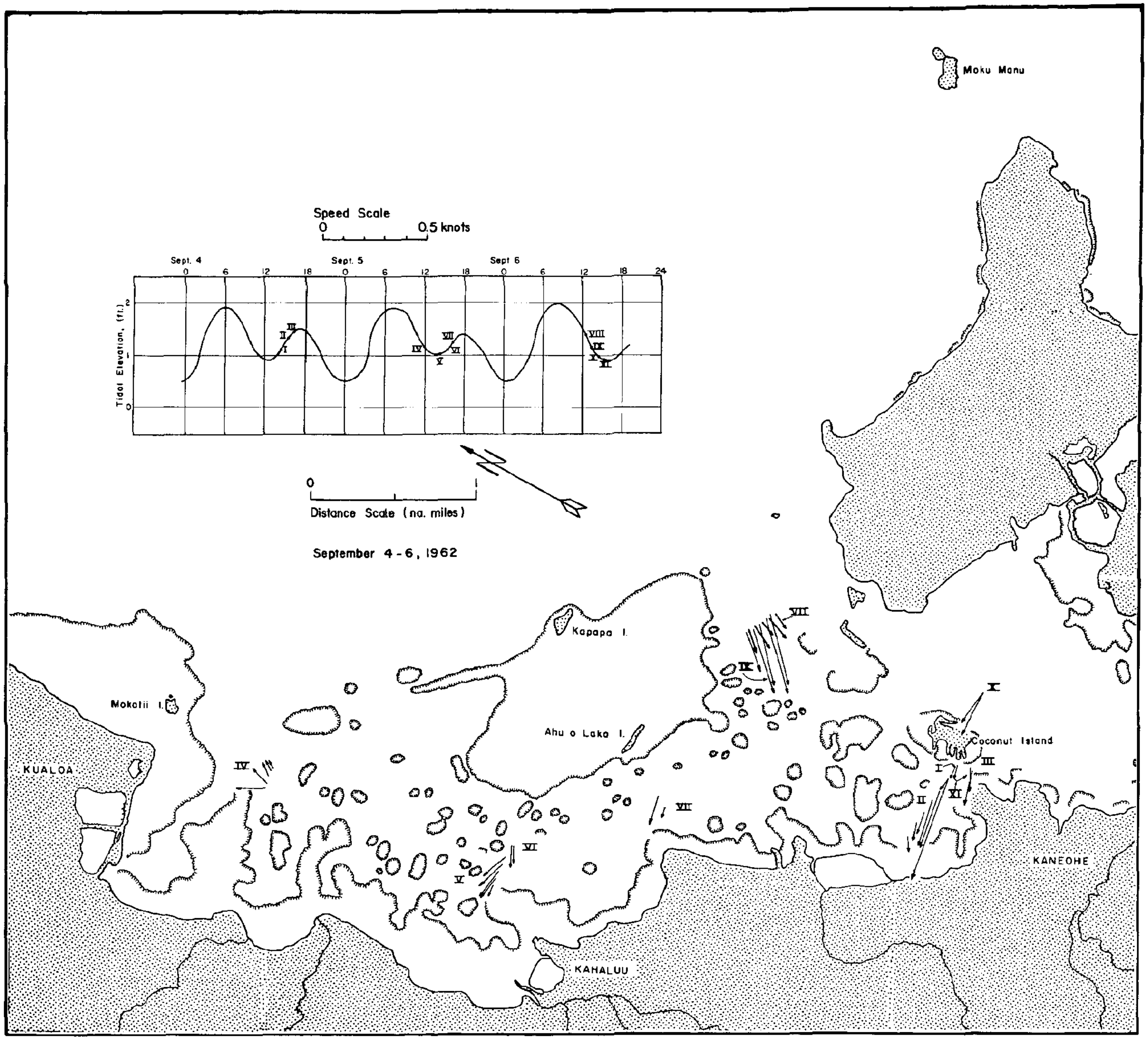


Fig. 14. Results of drogue measurements of currents in Kaneohe Bay, Oahu, September 4-6, 1962.

These observations are consistent with the location of the ebb-stage convergence somewhere northwest of Kailua, but suggest that the flood-stage divergence is generally southeast of Kailua.

In connection with the current surveys, a study was made of bacterial die-off as reported by Iha (1960). Even after allowing for dispersion the bacterial survival rate was only between .01 and .001 after 90 minutes. Details are discussed in section 7.3.

4.5 Waimanalo

Current measurements off Waimanalo have been made by the Hawaii Institute of Geophysics (see Figs. 15, 16, 17) and by Marine Advisers at various times for more than a year from September 1961 to October 1962. The results of these measurements show that the currents off Waimanalo are complex and with the available data it is difficult to fit them into a definite pattern with any degree of certainty.

Although northwesterly sets predominate the currents reverse at times especially in shallow water. Drogue measurements on September 11, 1962 (Fig. 15) show no reversals but a fluctuation in strength with tidal rhythm. The upper layers of water have a downwind component toward shore. This effect is most pronounced at the surface and has been noticed at all locations where this type of measurement has been made.

Drogue measurements on February 23, 1963 (Fig. 16) show currents with light trade winds blowing. The currents are weak, and since the one-meter drogues are moving up wind there certainly must be eddies here in the vertical plane as well as the horizontal. The southeast currents on the south side of Manana Island are representative of what Marine Advisers, Inc. found on several occasions. On January 31, 1962, and February 3, 1962, their drogues traveled from inshore of Manana Island clockwise around Makapuu Point. On the second date mentioned there was no wind. The drogues were picked up off Hanauma Bay with an apparent average speed of more than 1 knot.

Paddle-wheel current-meter observations in 80 feet of water on July 15-17, 1963 (Fig. 17) showed irregular current reversals.

Much of the difference in current patterns at Waimanalo at different times probably results from a shift in the position of the flood current divergence from Makapuu Point to somewhere northwest of Waimanalo. The consequence would be a change in the set of the flood current at Waimanalo from northwest to southeast. Eddying and other changes in the direction of the permanent flow are also probably involved.

4.6 Koko Head to Makapuu

Between Koko Head and Makapuu, the only current data available consists of drogue measurements obtained by Sunn, Low, Tom, and Hara on 8 April, 25 June, and 9 September, 1961 (Sunn, Low, Tom, and Hara, 1962b). These show a very clear and simple tide response. The flood flows, which set southwest, correspond in phase to the rising tide and the ebb flows, which set northeast, correspond in phase to the falling tide. Velocities as high as 1.5 knots for the flood current and 0.8 knot for the ebb current were measured, but these might have been somewhat intensified by wind drift associated respectively with a trade wind and a kona wind.

4.7 Maunalua Bay

Data from the paddle-wheel current meter set in 80 feet of water off Wailupe Peninsula (Aina Haina) in July 1963 (see Fig. 18) shows that a current pattern essentially like the one at Diamond Head holds for that

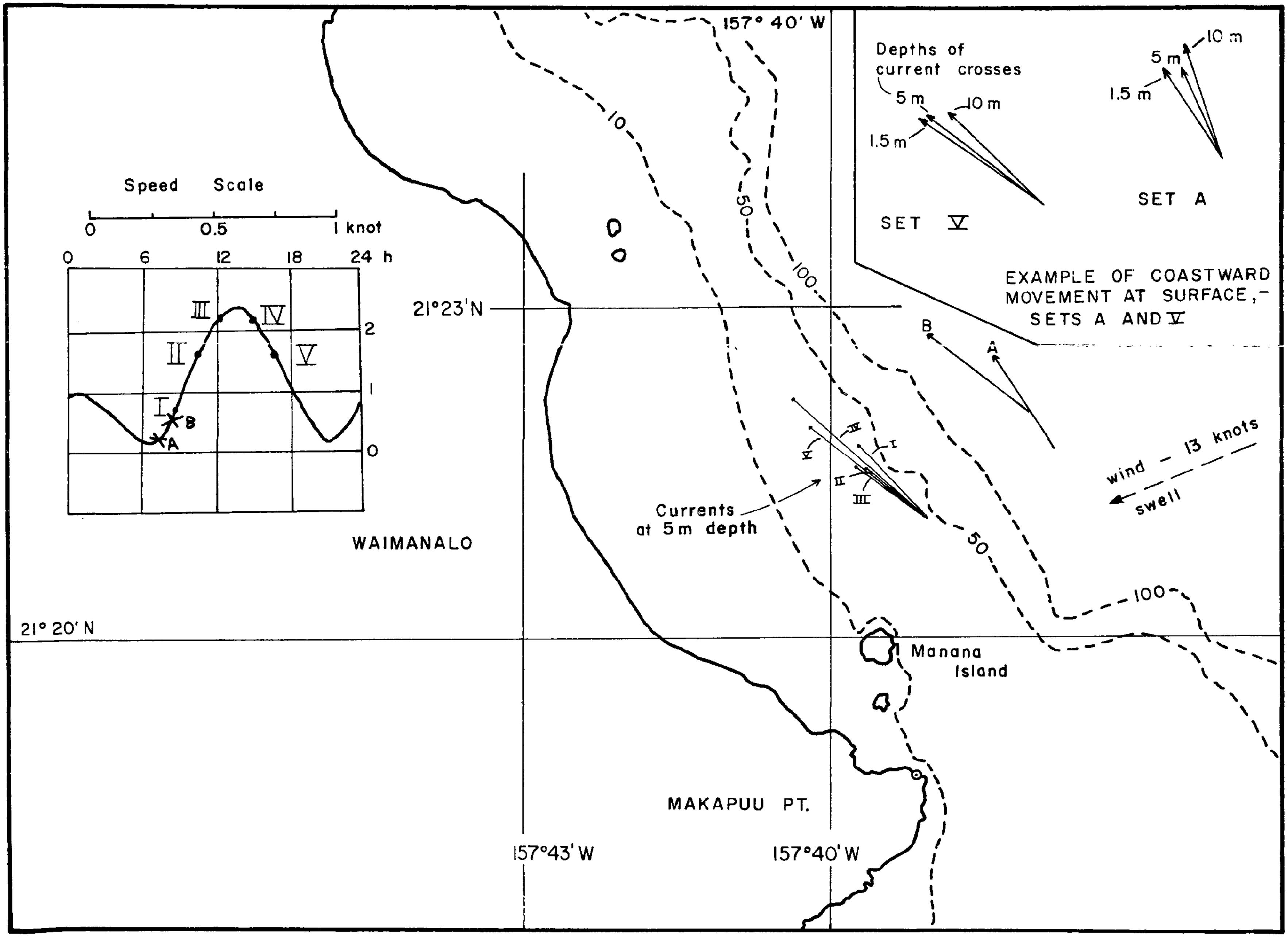


Fig. 15. Results of drogue measurements of currents off Waimanalo, September 11, 1962.

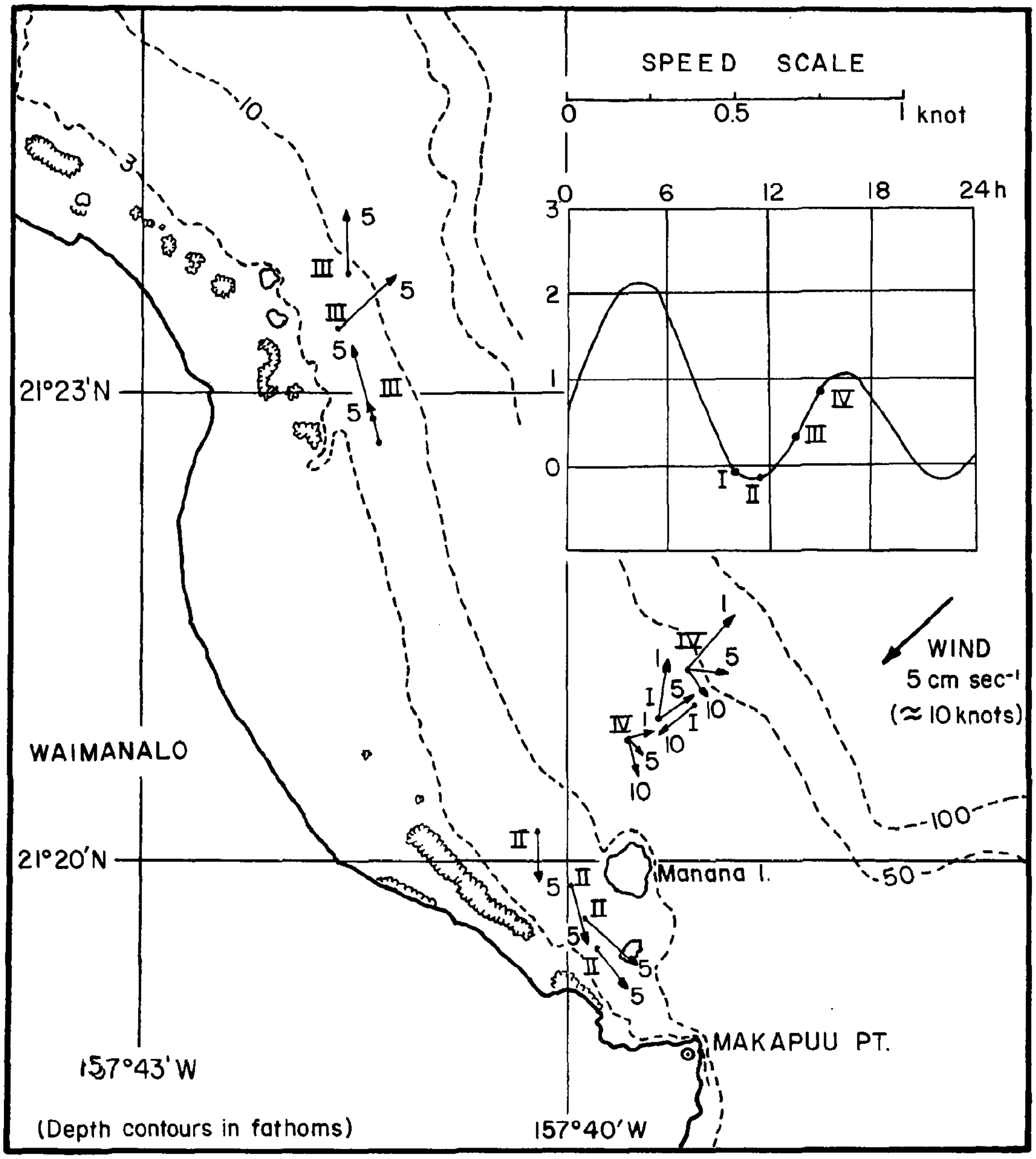
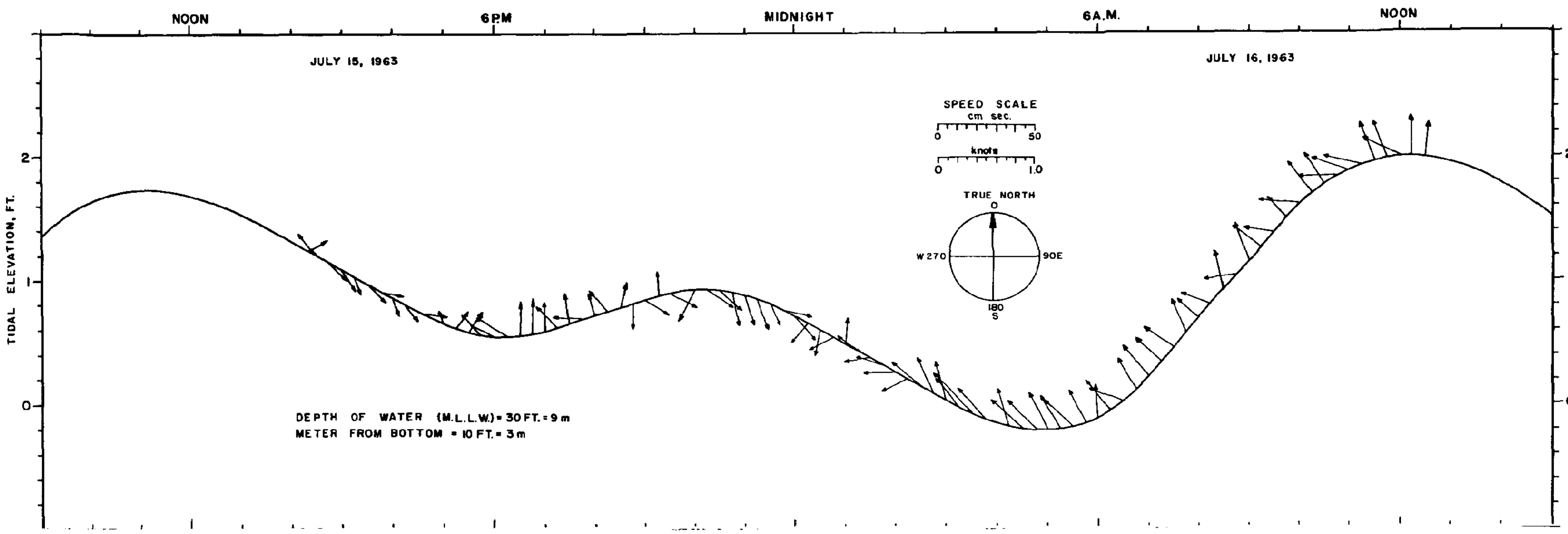


Fig. 16. Results of drogue measurements of currents off Waimanalo, February 23, 1963.



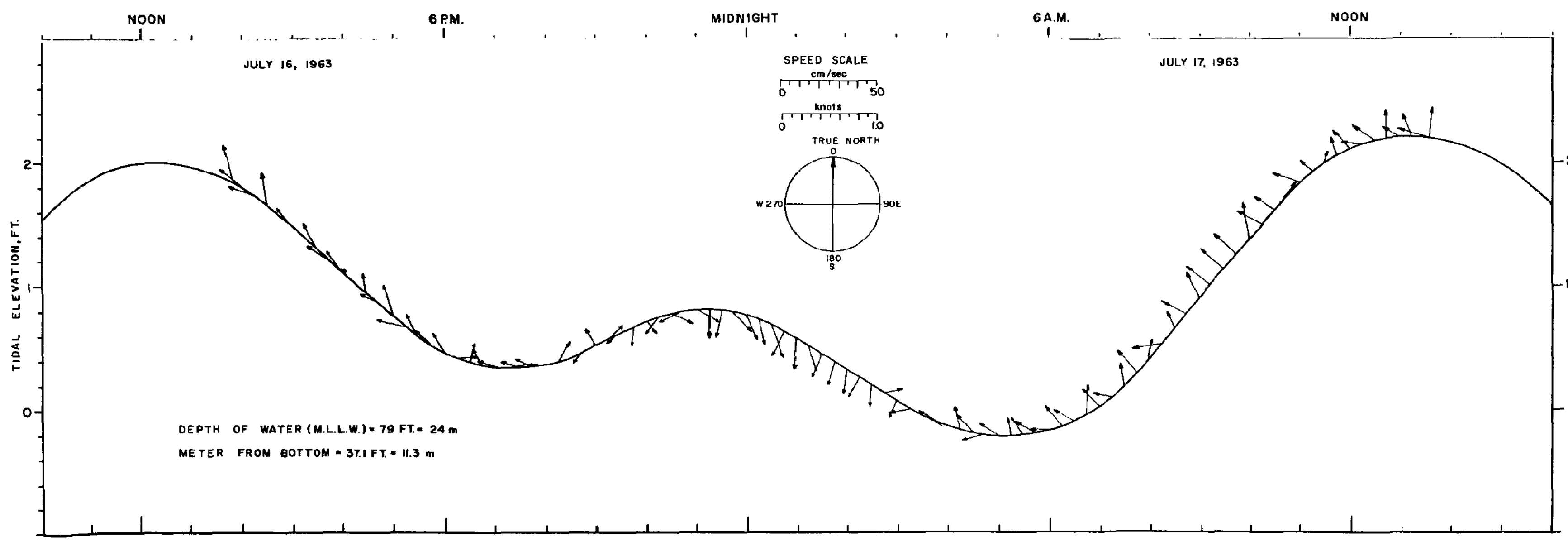


Fig. 17. Results of paddle-wheel current-meter measurements off Waimanalo, (top) July 15-16, (bottom) July 16-17, 1963.

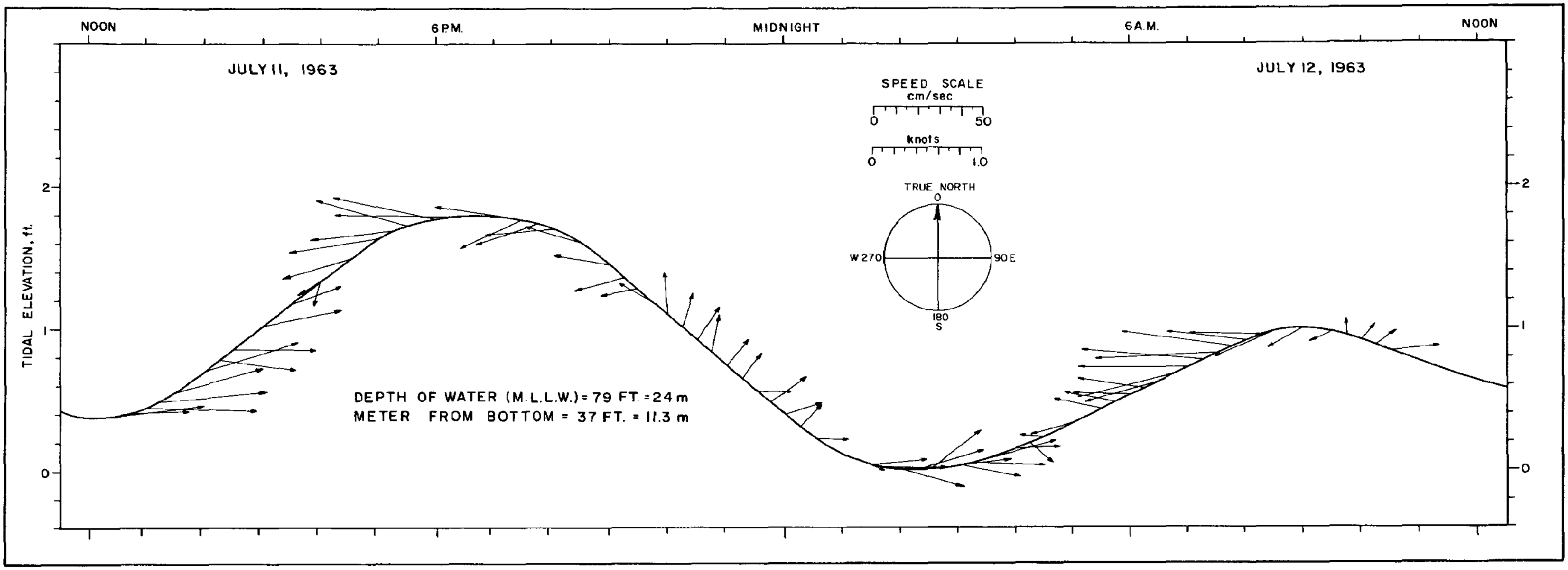


Fig. 18. Results of paddle-wheel current-meter measurements off Wailupe Pensinsula, July 11-12, 1963.

area and probably as far as Koko Head.

No current measurements were taken inside the bay near Kuliouou Beach Park. Here one would expect to find weak currents caused by eddies, currents caused by mass transport over the reef, and currents that are wind driven.

4.8 Mamala Bay

Mamala Bay is the broad indentation of the southern coast of Oahu lying between Diamond Head and Barber's Point. Into this bay open the Ala Moana Yacht basin, Kewalo basin, Honolulu Harbor via the Honolulu Channel and via the Kalihi Channel, and Pearl Harbor. Information on the currents of Mamala Bay has been derived from the following sources:

(a) Institute of Geophysics drogue studies off Diamond Head (Figs. 24, 25, 26, 27, 28, 29, 30).

(b) Engineering Experiment Station paddle-wheel current meter recording off Diamond Head continuously for nearly a month (Figs. 19, 20).

(c) Institute of Geophysics drogue studies off Waikiki (Figs. 26, 27).

(d) H.A.R. Austin and Associates and Law and Wilson (1961) drogue studies off Ala Moana.

(e) Engineering Experiment Station paddle-wheel current-meter study off Magic Island (Fig. 21, top).

(f) Engineering Experiment Station paddle-wheel current meter study off Kewalo Basin (Fig. 21, bottom).

(g) Institute of Geophysics drogue studies off Kewalo and Honolulu Harbors (Figs. 26, 27, 28, 29, 30).

(h) Bureau of Sanitation (1941) studies of bacterial concentrations off the former Kewalo sewer outfall (Fig. 33).

(i) Metcalf and Eddy (1944) studies of bacterial concentration and slick fields from the former Kewalo outfall.

(j) Division of Sewers (1951) drogue studies near the Sand Island sewer outfall.

(k) Hyperion Engineers (1957) calculations based on the Division of Sewers (1952) studies.

(l) Austin, Smith, and Associates (1961b)observations on the slick field from the Sand Island outfall.

(m) Institute of Geophysics measurements of turbidity from the Sand Island outfall (Figs. 31 and 32).

(n) Engineering Experiment Station paddle-wheel current measurements and dye studies in the vicinity of the Sand Island outfall. (Fig. 22).

(o) Austin, Smith, and Associates (1960) drogue studies off Pearl Harbor.

(p) Institute of Geophysics drogue studies off Pearl Harbor.

(q) Institute of Geophysics drogue studies off Ewa (Fig. 34).

(r) Institute of Geophysics paddle-wheel current-meter study southeast of Barber's Point (Fig. 23).

The Institute of Geophysics current-meter study northwest of Barber's Point, although not in Mamala Bay, is also of critical importance in understanding the current behavior in the Bay.

Off Diamond Head the paddle-wheel current meter measurements continued by Tinniswood and Avery over a period from 24 November to 19 December 1963 indicate the predominance of tidal currents. Figure 19 shows some samples of the records obtained. The flood current, which persists during the rise

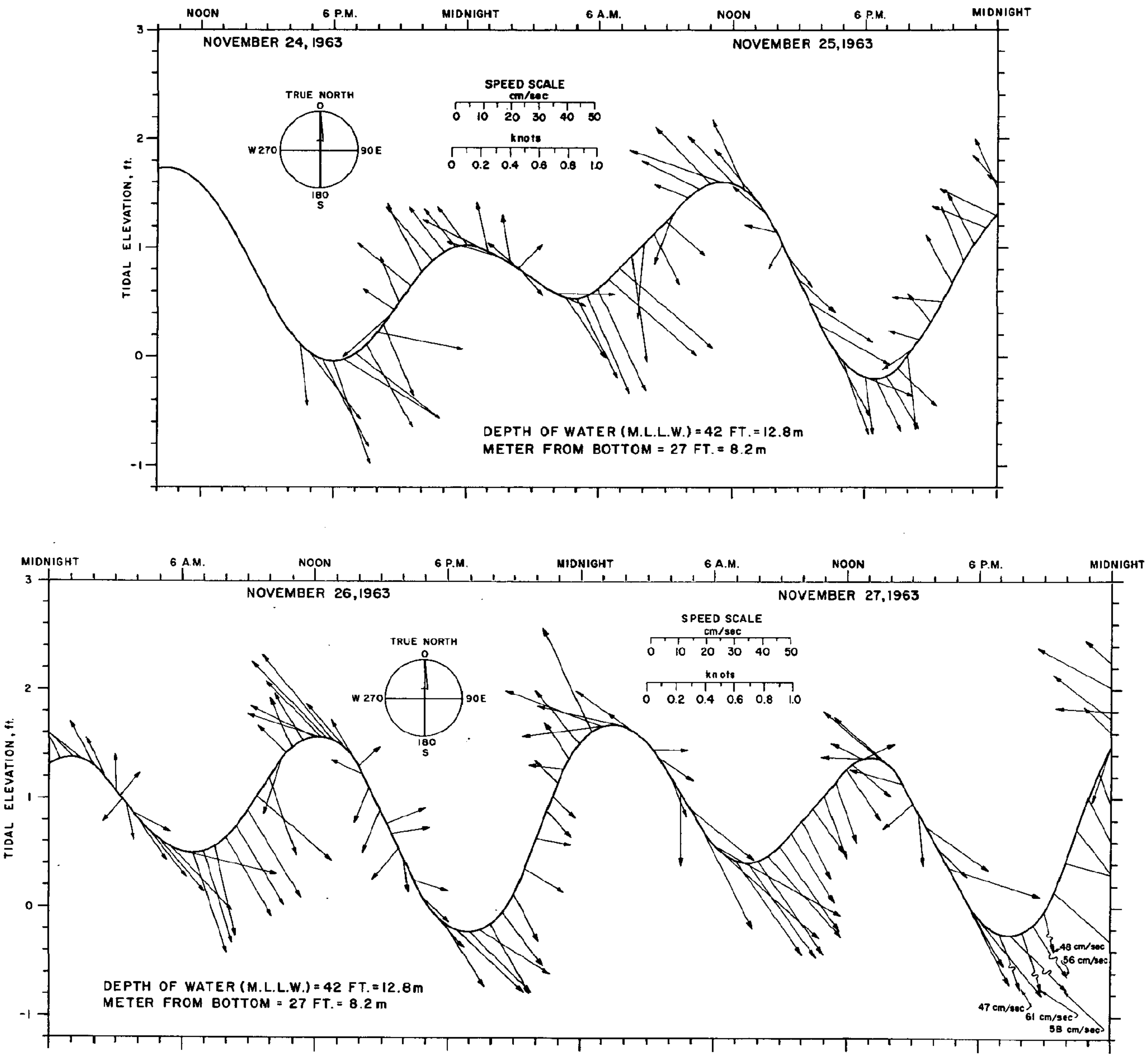


Fig. 19. Results of paddle-wheel current-meter measurements off Diamond Head, (top) November 24-25, (bottom) November 26-27, 1963.

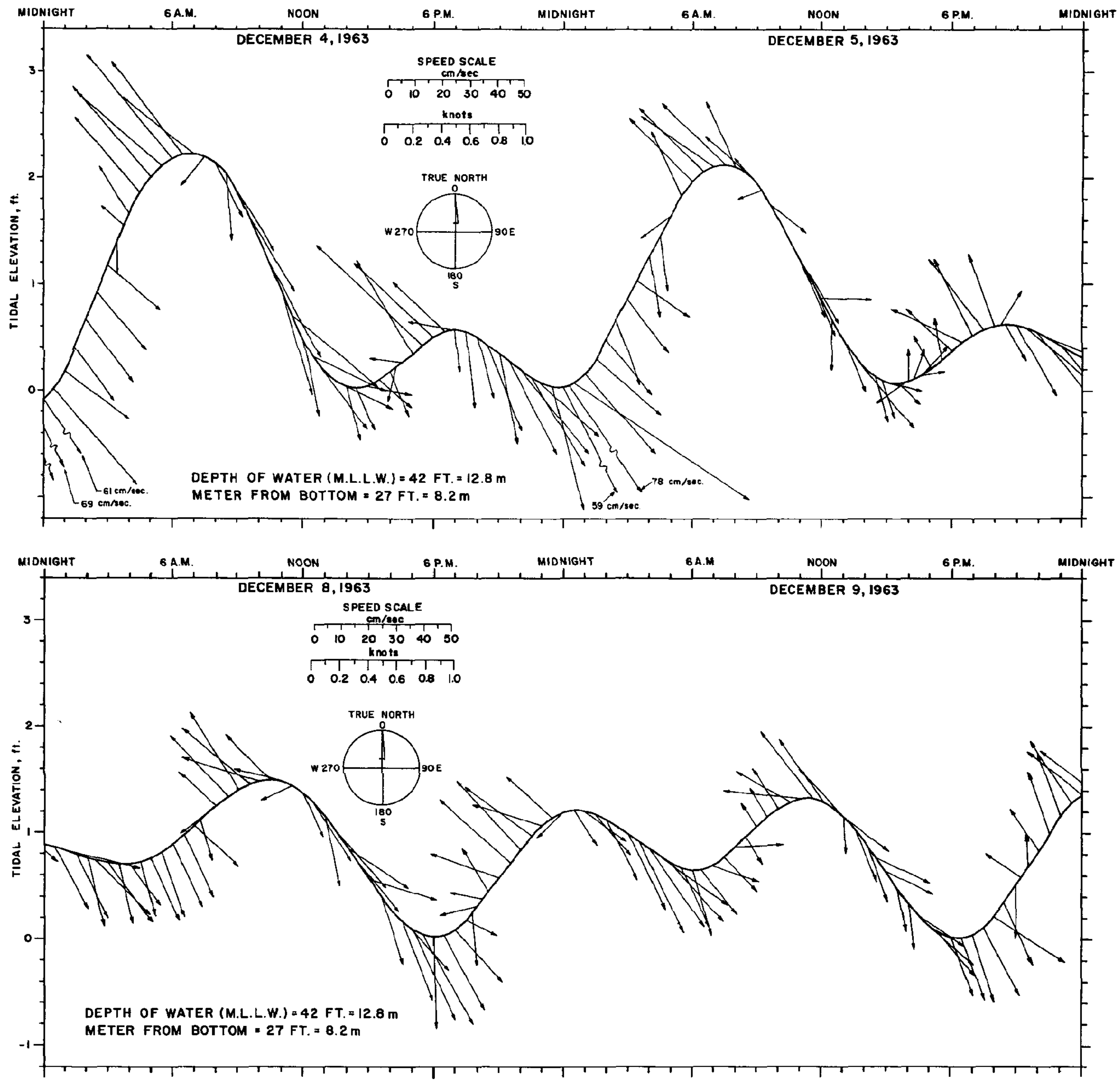


Fig. 20. Results of paddle-wheel current-meter measurements off Diamond Head, (top) December 4-5, (bottom) December 8-9, 1963.

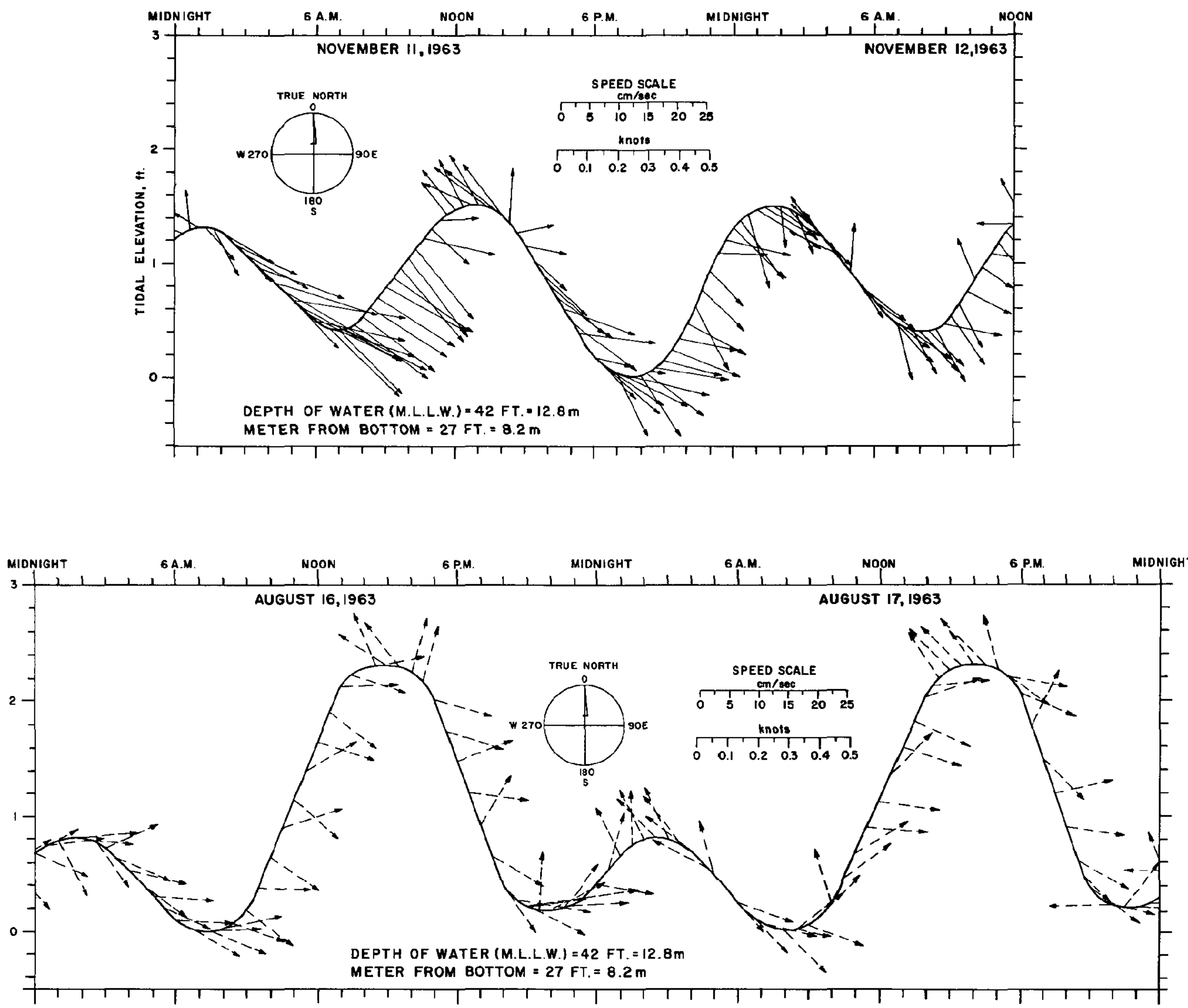


Fig. 21. Results of paddle-wheel current-meter measurements off Magic Island, (top) November 11-12, 1963, and off Kewalo, (bottom) August 16-17, 1963.

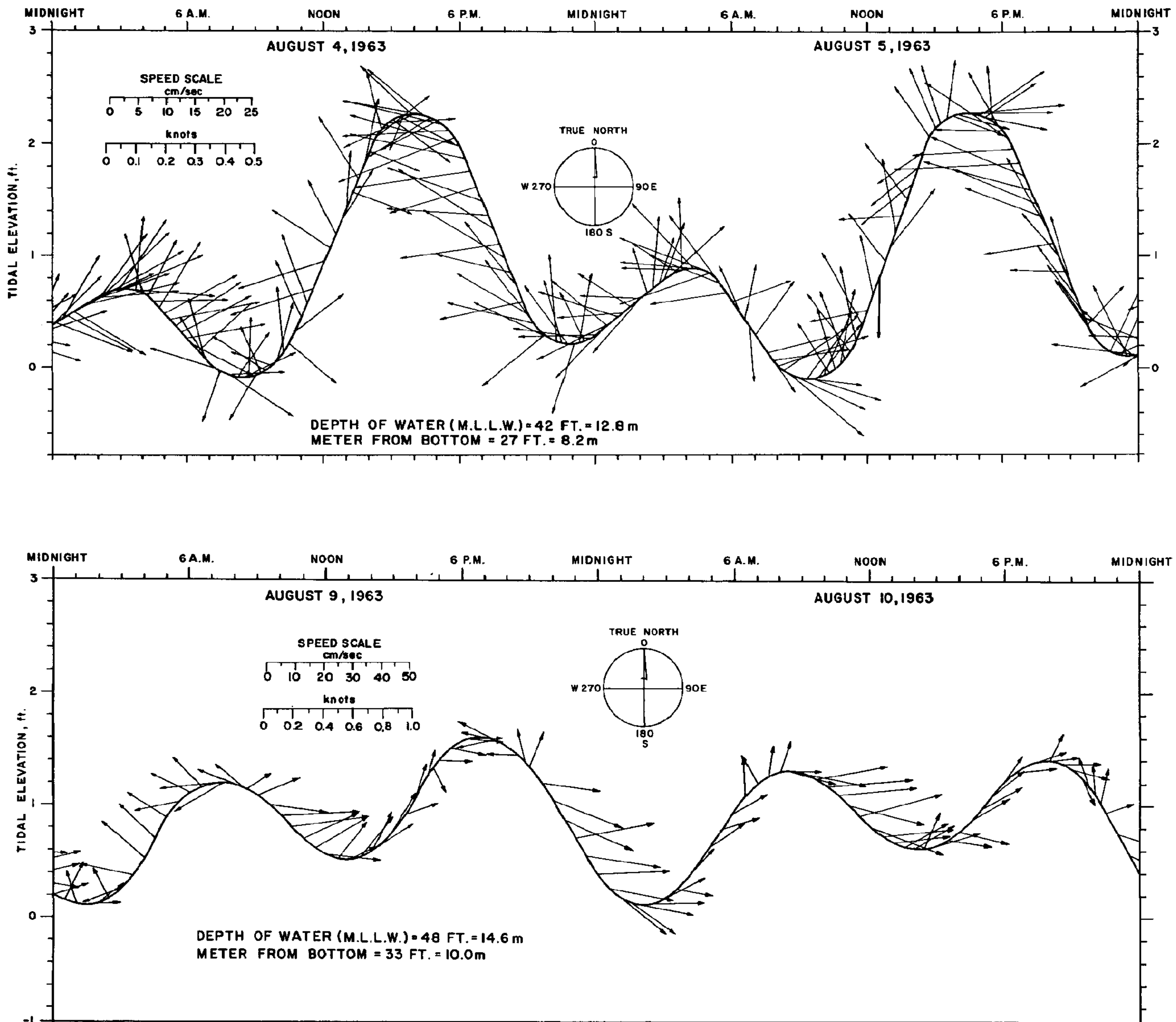


Fig. 22. Results of paddle-wheel current-meter measurements near Sand Island sewer outfall, (top) August 4-5, (bottom) August 9-10, 1963.

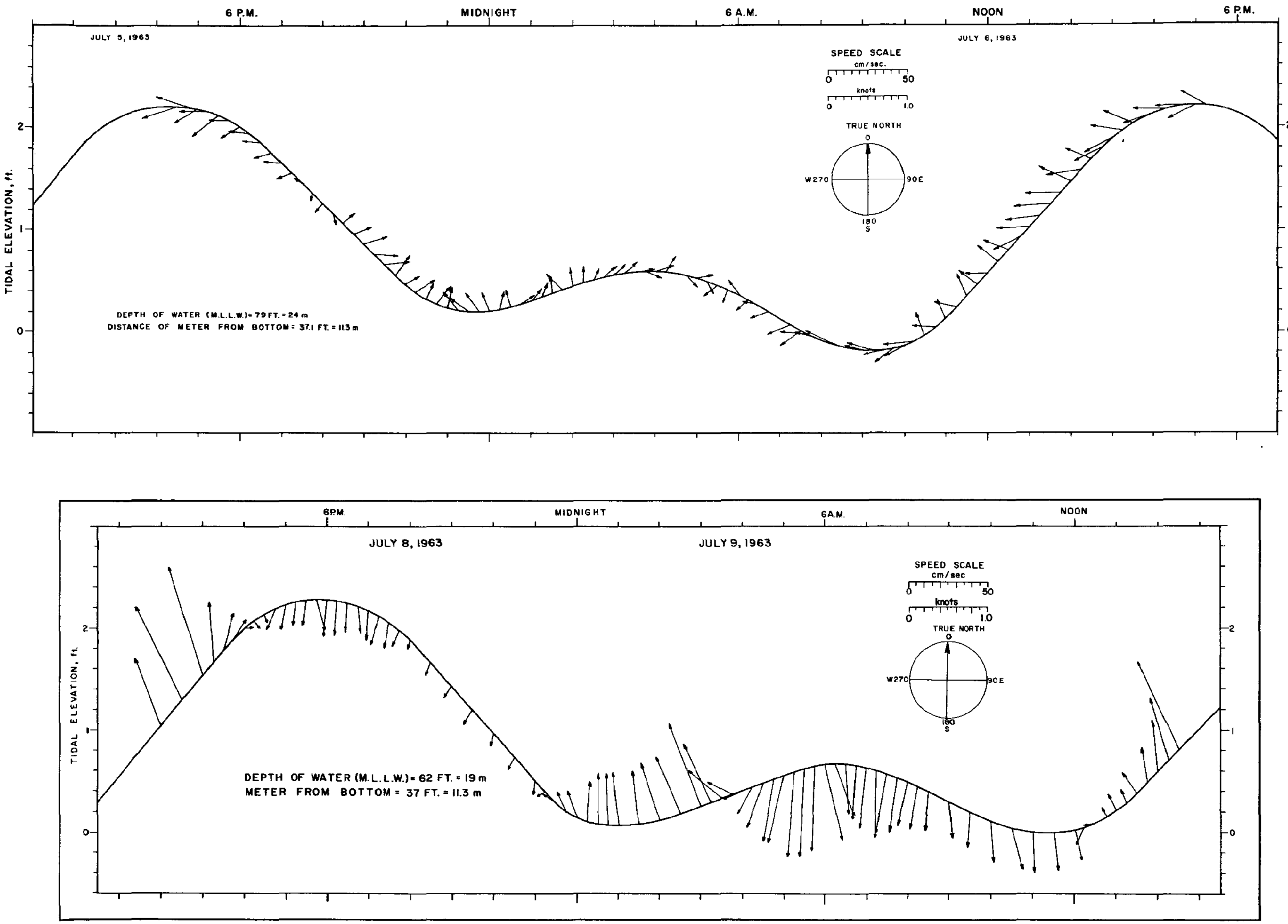


Fig. 23. Results of paddle-wheel current-meter measurements (top) southeast of Barbers Point, July 5-6, 1963, and (bottom) northwest of Barbers Point, July 8-9, 1963.

of the tide and at the time of high tide, sets northwest in accordance with the theory discussed in section 2.4. The ebb current has the reverse set. The average velocity is approximately 0.6 knot. Characteristically the ebb velocity is greater than the flood velocity, and the ebb current before a large tide rise has reached a maximum of more than 2 knots. An offshore set during the turn of the current may be partly the effect of the winds, although it was also noted during the calm weather that predominated during the period of the current meter measurements. The records appear sufficiently regular to encourage the belief that harmonic analysis will provide the basis for useable current predictions. Drogue measurements made off Diamond Head at various times agree with the current-meter measurements and provide, as well, some additional information to be discussed elsewhere.

Less extensive paddle-wheel current measurements made about $1\frac{1}{2}$ miles northwest of Barbers Point in July 1963 show similar although somewhat less regular results (Fig. 23, bottom), with the flood current setting south and the ebb current setting northwest, as discussed in more detail in section 4.12. Still more irregular paddle-wheel current-meter results were obtained a few days earlier about 3 miles east-southeast of Barbers Point as shown in Figure 23 (top). Velocities averaged about 3/4 knot and reached a maximum of about $1\frac{1}{2}$ knots. Drogue measurements made in the same area in April 1963 indicate that a major part of the irregularity results from the formation of eddies especially from the swing of the flood current around the Point.

Apparently the area of convergence of the flood current and the area of divergence of the ebb current must lie somewhere between Diamond Head and Barbers Point, in other words somewhere in Mamala Bay. It is not surprising that the current patterns in the Bay are complex and irregular.

Between Sand Island and Diamond Head the currents generally show some similarities in phase to the currents at Diamond Head, although the velocities are lower and the irregularities increase toward Sand Island. Figure 26 summarizes drogue measurements in the area made during predominantly flood-current phases in 1962, and Figure 27 similarly summarizes measurements for the ebb phases. Figures 28, 29, and 30 show the results of additional drogue measurements in February and March 1963 in relation to tide phases. Altogether more than 80 drogue settings were made in this area. Exceptions to the general westerly set of the flood current and easterly set of the ebb current are found in sets III and V on 24 February (Fig. 28) and set VI on 3 March (Fig. 29). These sets are in shallow water and the reversals are probably due to eddies.

A comparison of Figures 29 and 30 shows that the strength of the tidal current is not always simply correlated with tidal amplitudes. It is also apparent, from Figure 28, that the change of direction of tidal current can occur at different times within short distances in the area west of Waikiki (cf. Fig. 28, sets IV, V, and VI). As a result of the complex current pattern and owing to the effect of variations in phase of currents in shallow and deep water, currents in opposite directions can exist within relatively small horizontal distances (see for example Fig. 29, sets A and B).

The effects of wind and mass transport were observed to depths of several fathoms in most measurements involving drogues set at several depths. However, except in direct wind-drift effects, only minor differences have been found between trade and kona conditions.

Drogue measurements by H. A. R. Austin and Law and Wilson (1961) in

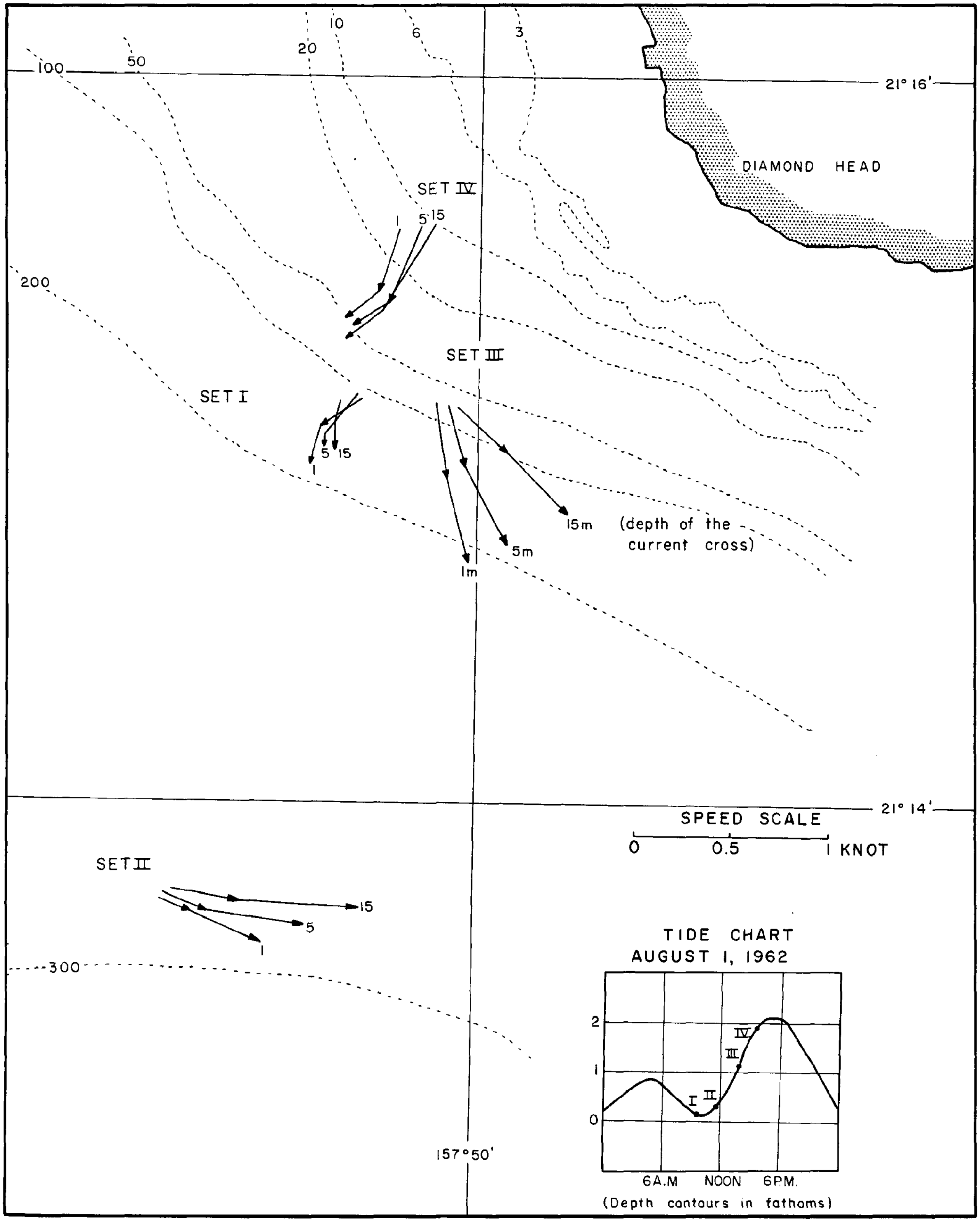


Fig. 24. Results of drogue measurements of currents off Diamond Head, August 1, 1962, showing effect of wind drag and mass transport.

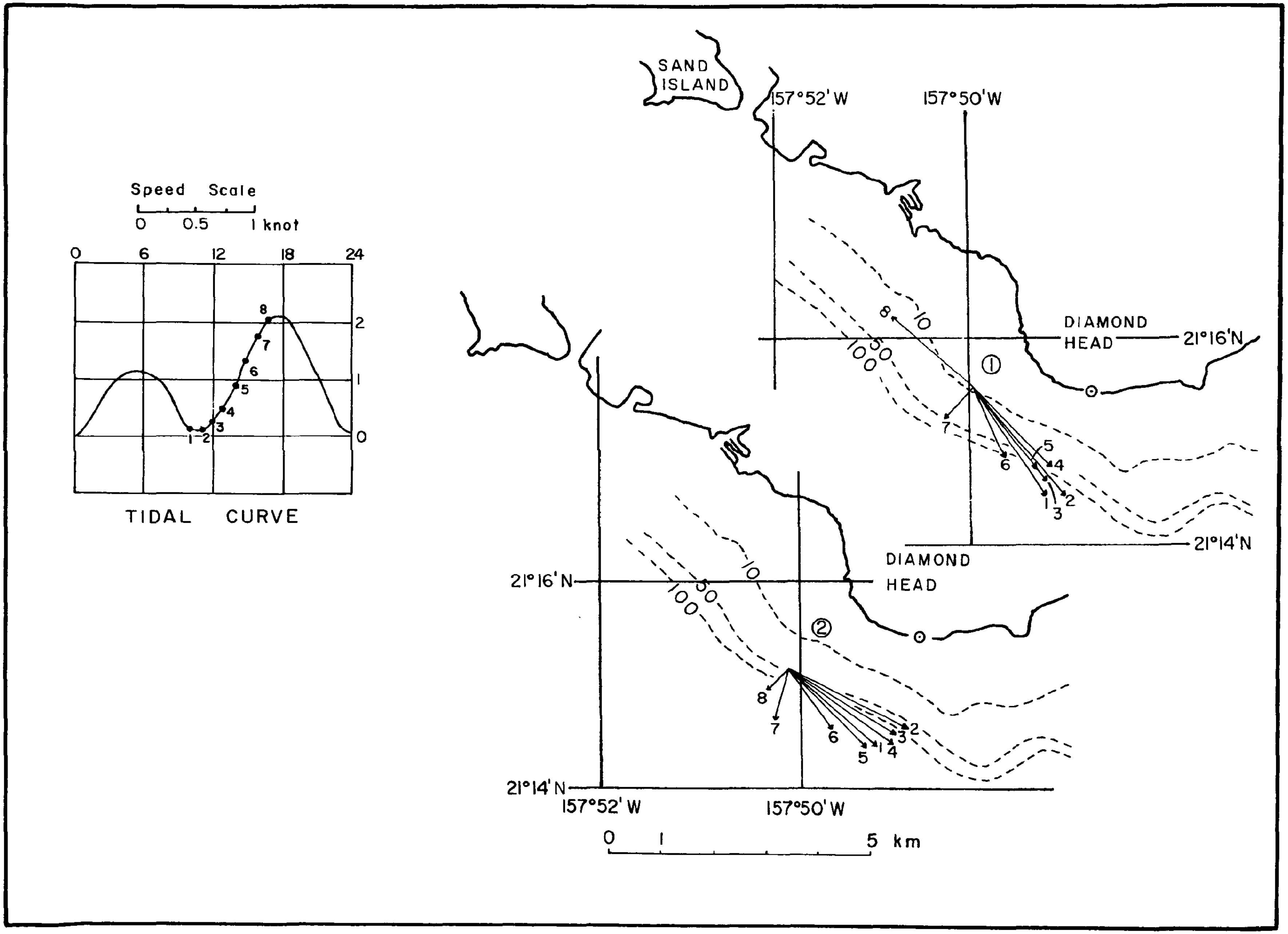


Fig. 25. Results of drogue measurements of currents off Diamond Head, August 17, 1962. Quasi-simultaneous observations at two stations.

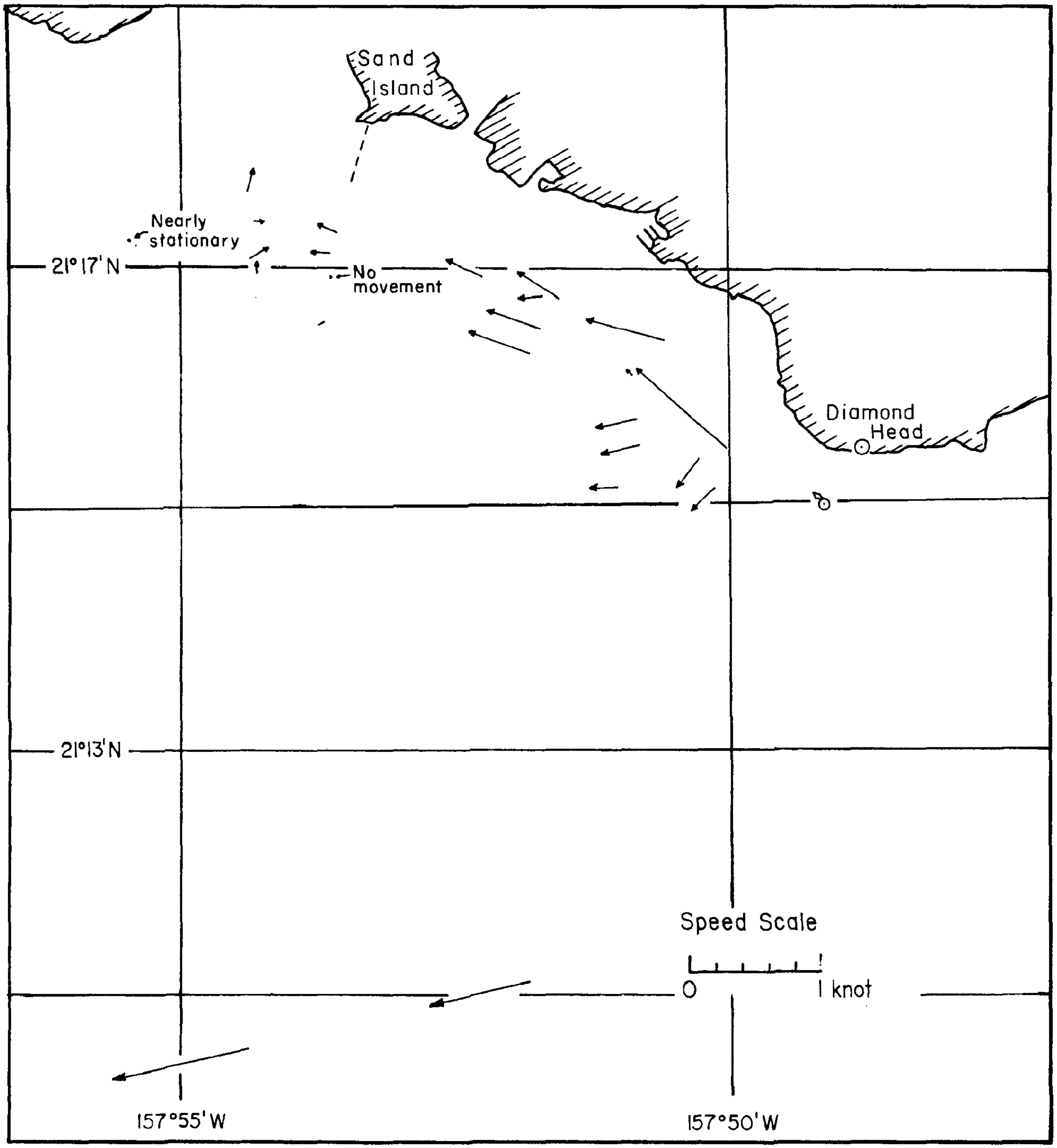


Fig. 26. Results of drogue measurements of currents in the eastern part of Mamala Bay in 1962 during predominantly flooding currents.

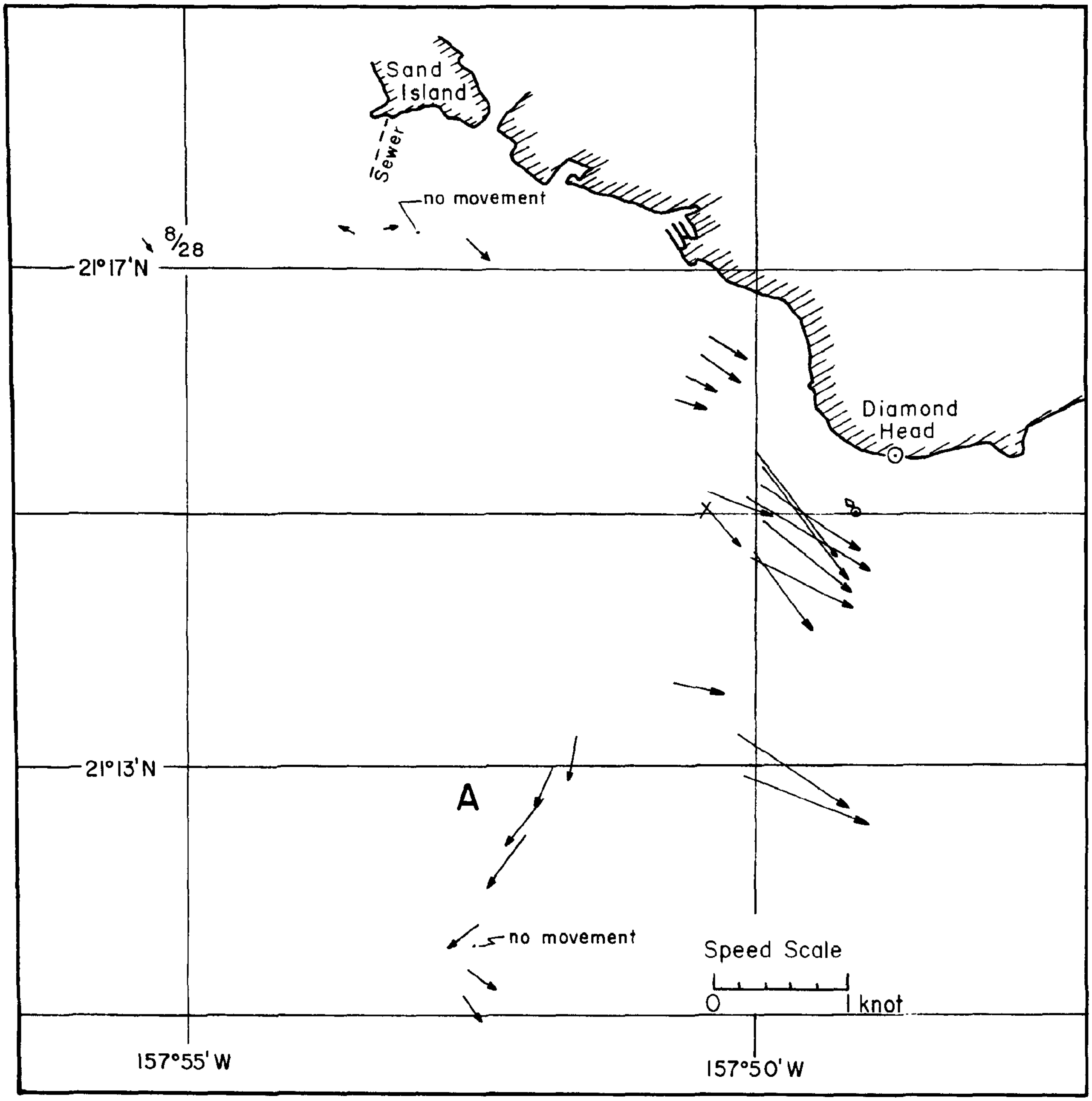


Fig. 27. Results of drogue measurements of currents in the eastern part of Mamala Bay in 1962 during predominantly ebbing currents.

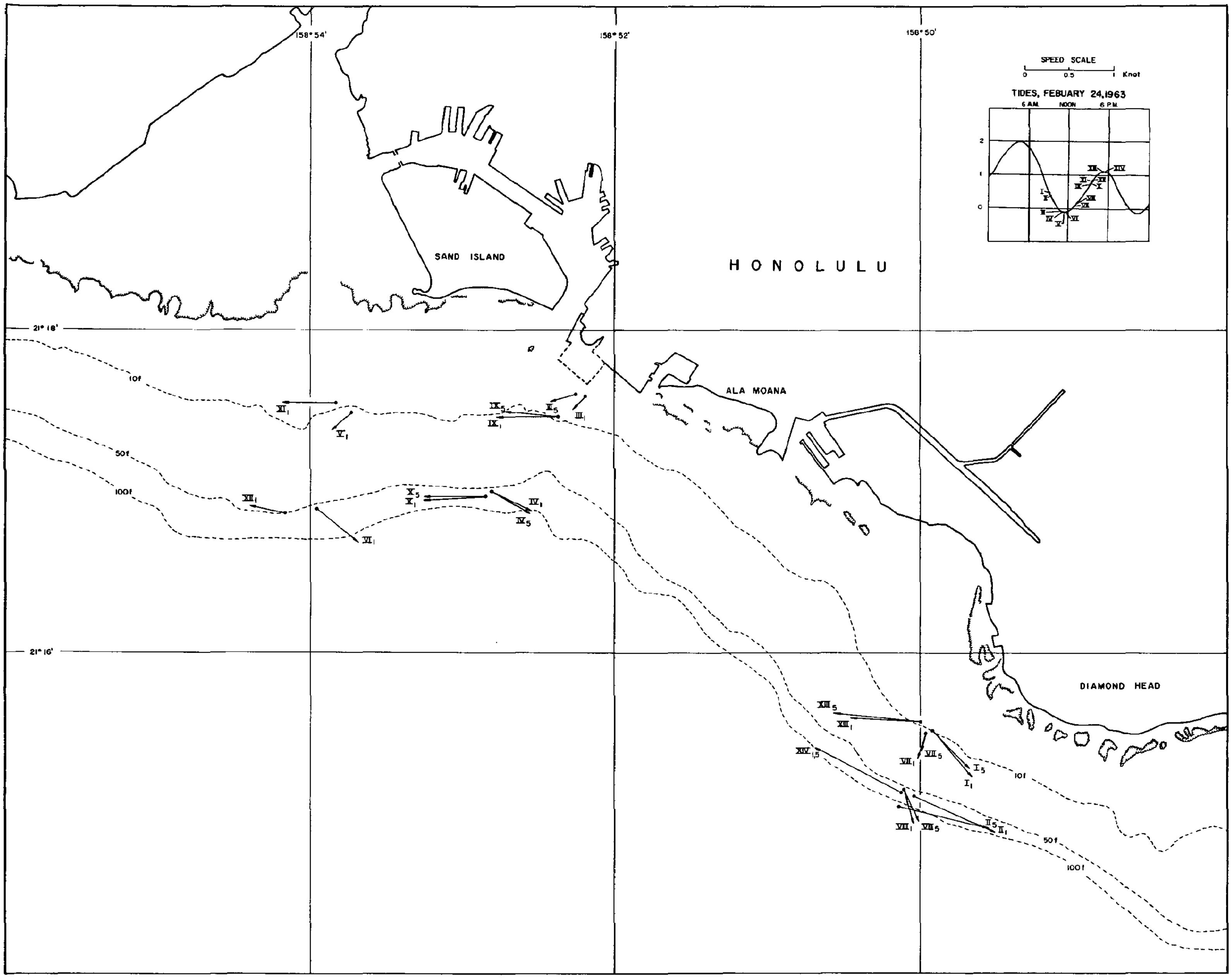


Fig. 28. Results of drogue measurements of currents in the eastern part of Mamala Bay, February 24, 1963.

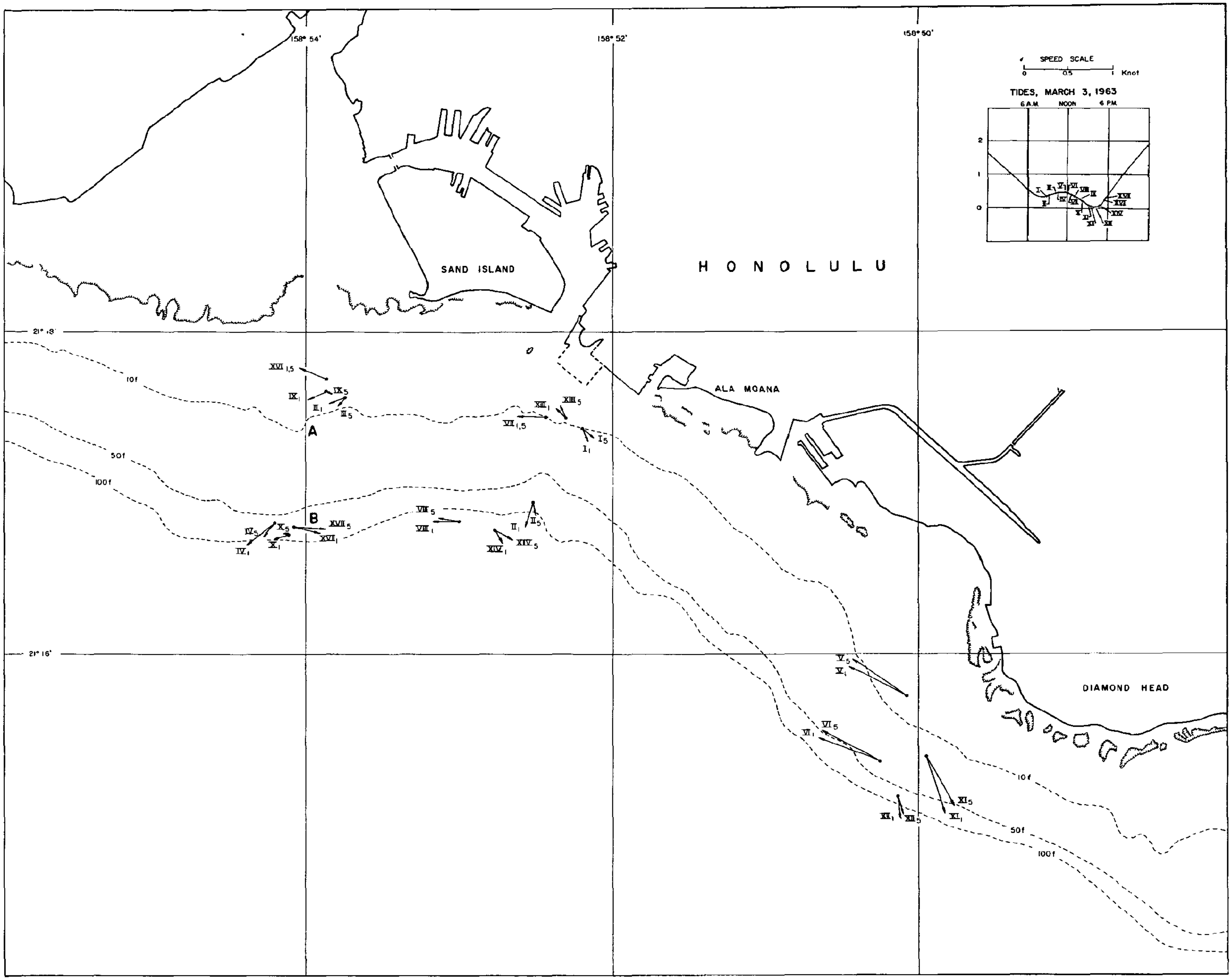


Fig. 29. Results of drogue measurements of currents in the eastern part of Mamala Bay, March 3, 1963.

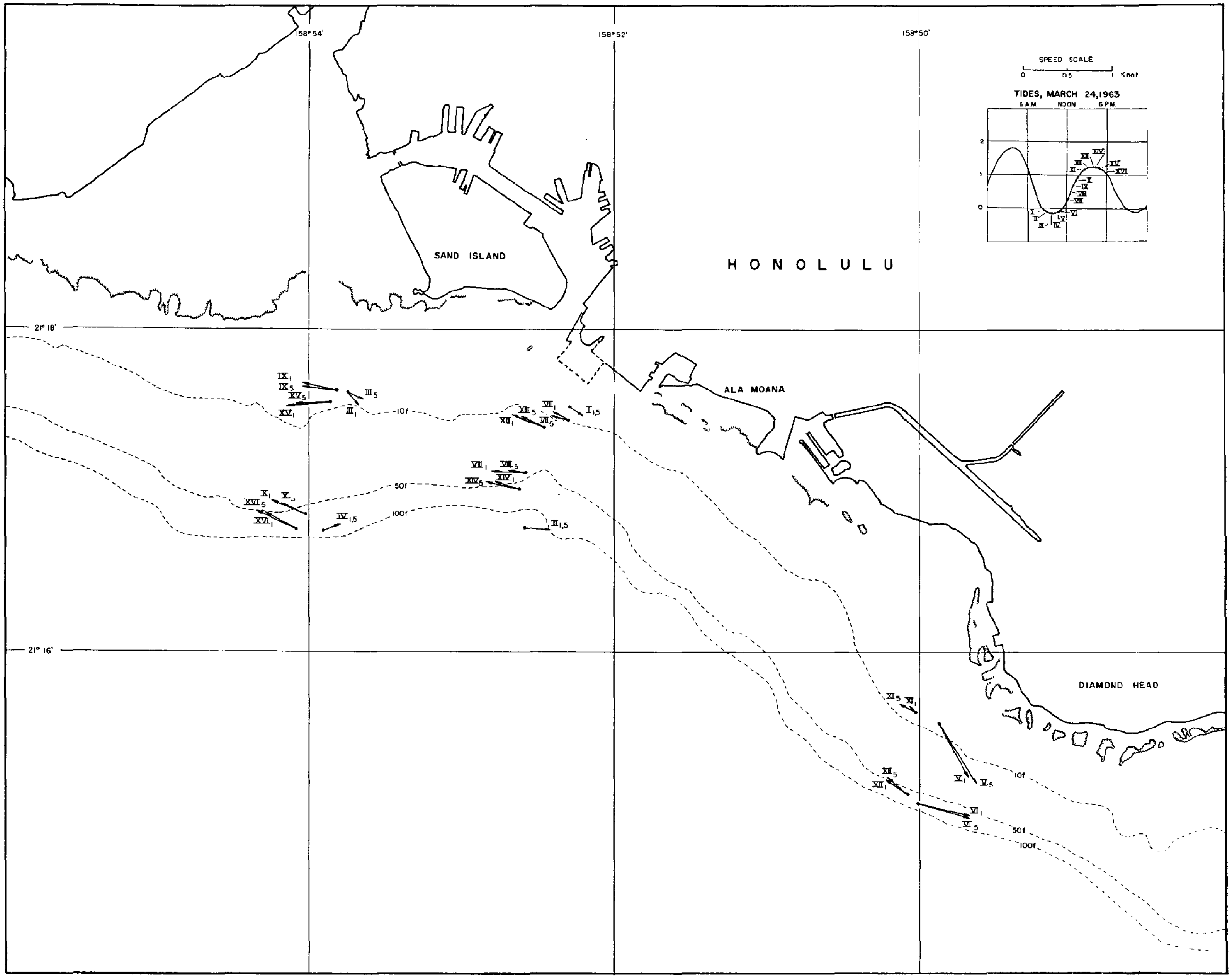


Fig. 30. Results of drogue measurements of currents in the eastern part of Mamala Bay, March 24, 1963.

front of the Ala Moana reef show quite consistent tidal-current reverses with the current setting north-northeast on the rising tide and south-southwest on the falling tide. The apparent reversal of phase may be the result of eddies consistently set up by both the flood and ebb current. The velocities measured for the south-southwesterly current sometimes exceeded 1 knot, considerably greater than those measured for the reverse current but the differences are probably the result of trade wind effects on the floats as well as trade wind-induced surface current.

Dye and current-meter studies conducted by Tinniswood and Avery in the vicinity of the Sand Island sewer outfall during trade-wind weather indicate that the sewage may be carried either toward Diamond Head or toward Barber's Point. The paddle-wheel current meter showed a reversing current with some tendency to follow the Diamond Head pattern, but with stronger superimposed erratic currents that probably represented eddies. Velocities averaged about 0.2 knot and reached a maximum of about 0.4 knot. On one occasion, the paddle-wheel current meter showed that the current at the sewer outlet, 15 feet below the surface, flowed continuously for 51 hours in the general direction of Waikiki; and, on another occasion, dye was followed from the sewer outlet in mid-morning to just off the Kewalo Channel by mid-afternoon. With the trade winds blowing, the surface layer moves with an offshore component that should carry floatables out to sea, but, with a kona wind blowing, the same process would carry the floatables shoreward.

Additional tracer studies have used turbidity as the trace material. Figures 31 and 32 show the distribution of turbidity in the eastern part of Mamala Bay respectively during an ebbing current under kona conitions and during a predominantly flooding current under trade-wind conditions.

It should be noted that the distributions shown represent specific tide conditions and cannot be taken as averages. In Figure 31 a tongue of high turbidity at (A) results from the flow of sewage southwestward from the sewer outfall. Another tongue of high turbidity water at (B) may represent the outflow of turbid water from the Kalihi Channel. A tongue of clear water (C), from farther off shore, is flowing along the slope towards Waikiki. A sharp gradient in the concentration of pollutant is indicated by the turbidity measurements over the slope at (D).

In Figure 32 the sewage flows at point (A) towards Pearl Harbor with a slight offshore component. A tongue of clear water flows in the same direction at (B) farther offshore. However, there are two concentrations of polluted water at points (C) and (D) still farther offshore over the slope. These have probably resulted from previous injections of sewage during periods of relatively low current velocity past the sewer outlet. Their distribution suggests that the net flow past the outlet first set toward the west and then swung toward the southeast during the few tide cycles that preceded the measurements.

Similar studies were made by Tay monthly from June 1940 to September 1941 (Bureau of Sanitation, 1941) and by Metcalf and Eddy (1944) monthly from April to July 1944 using bacterial concentrations from the old Kewalo sewer outfall as tracers. Because of the nature of the sampling program the results cannot be expected to show fine detail, and times and tide stages at the times of collection are not indicated. Nevertheless the studies are extremely valuable because of the range of time and conditions they span. Metcalf and Eddy found that the contaminated water from the Kewalo sewer was moving only to the west or offshore, but Tay generally found a tongue of contaminated water moving eastward. The greatest

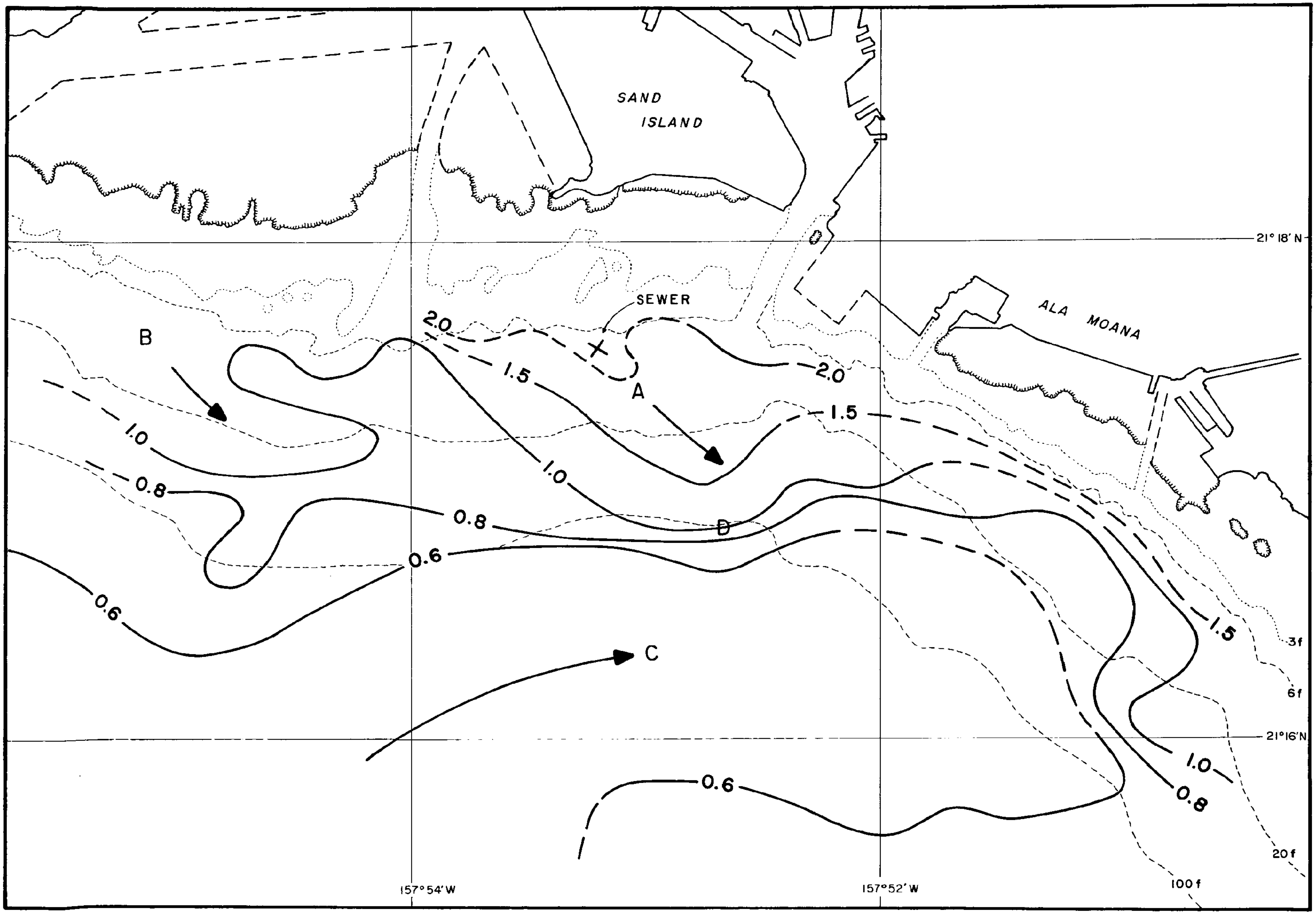


Fig. 31. Distribution of turbidity off Sand Island and Ala Moana on December 28, 1962, during a predominantly ebbing current.

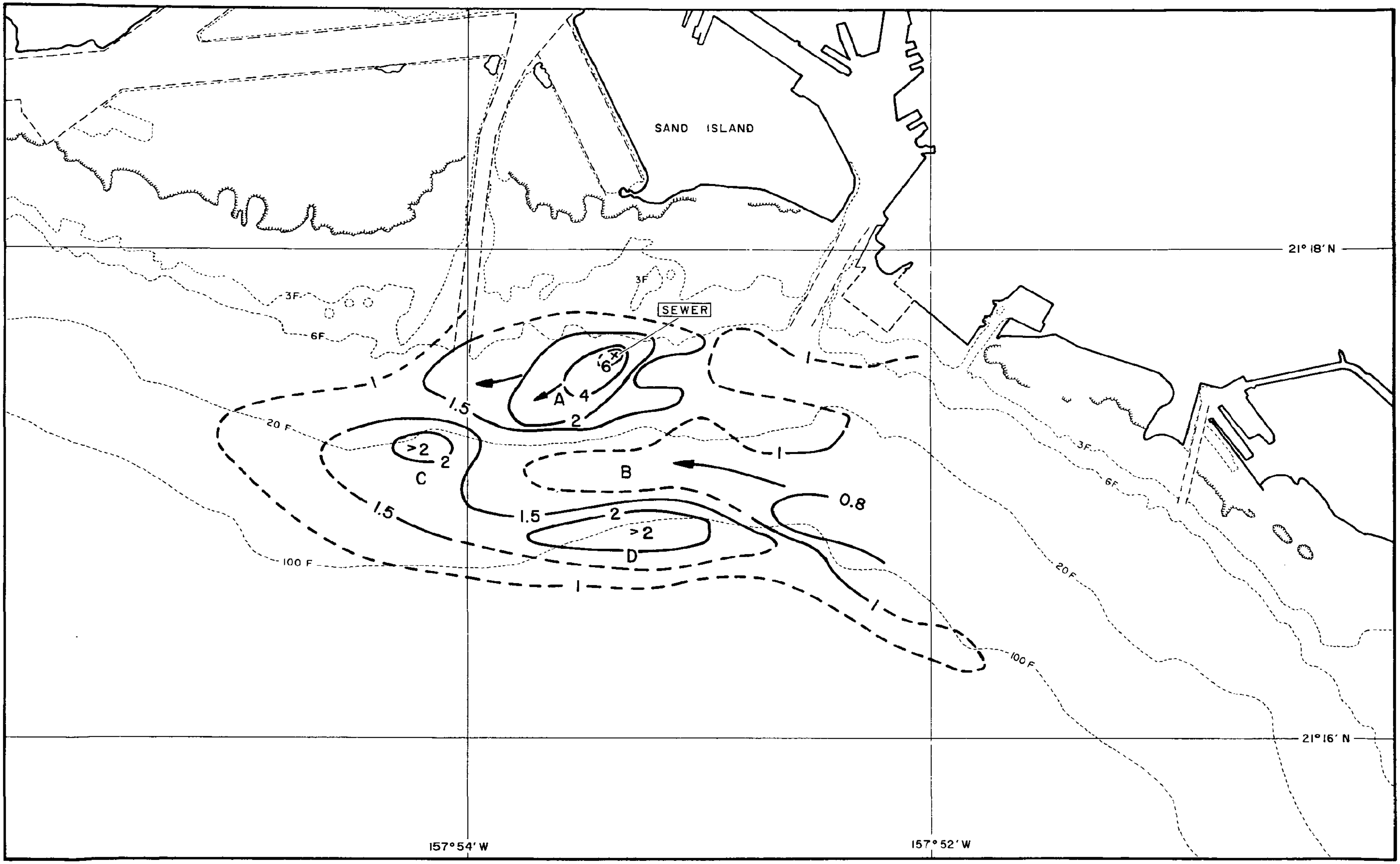


Fig. 32. Distribution of turbidity off Sand Island and Ala Moana on July 17, 1963, during a predominantly flooding current.

eastward flow was in February 1941 (Fig. 33) when there was a concentration of Bacterium coli greater than 1000 per 100 ml one mile off Kuhio Beach and a concentration greater than 100 per 100 ml 0.25 mile off the natatorium.

It seems inescapable that sewage from the Sand Island outfall must at one time or another be carried to all parts of Mamala Bay, and that it must at times enter Keehi Lagoon, Honolulu Harbor, and probably inshore areas farther east.

Drogue measurements by Austin, Smith, and Associates (1960) off the Pearl Harbor entrance and Hickam Field showed some tidal response, generally in phase with that at Diamond Head, but dominance by some other component that set continuously southwest during the six days of the study in February, March, and April 1960, and on one day in December 1958, and that set northeast in two other days in December. The latter component probably involves wind drag. Wind data were not given for the times of the measurements, but it seems probable that kona winds prevailed on the two days when the set was northeast and trade winds on the other days.

4.9 Ala Wai to Kewalo

Prior to the construction of the Ala Wai Yacht Harbor channel and the isolation of Kewalo Basin from the channel along the front of Ala Moana Park, there was a strong, unidirectional current flowing from the Ala Wai canal through the Yacht Harbor, augmented in the Ala Moana Park channel by water carried by mass transport over the reef, continuing through Kewalo Basin and out to sea through the Kewalo channel.

Since the Ala Wai Yacht channel was dredged, and the channel along the front of Ala Moana Park was blocked off from both the Yacht Harbor and Kewalo Basin, the Ala Wai canal water has drained seaward through the yacht channel. Groundwater and storm-sewer discharge continues to flow seaward through the Kewalo channel, however. Float studies by H. A. R. Austin and Associates and Law and Wilson (1961) show that the seaward currents in both the Ala Wai and the Kewalo channels have velocities on the order of 0.1 to 0.2 knot. There continues to be a slight westward flow in the Ala Moana Park channel, probably resulting from a combination of mass transport over the reef and wind drag in the channel.

In the "Magic Island" channel configuration planned for construction on the Ala Moana reef (H.A.R. Austin and Associates and Law and Wilson, 1961), mass transport over a weir at the east entrance to the channel will be counted on to flush the channel westward.

4.10 Honolulu Harbor - Keehi Lagoon

There seems to be practically no information on currents in Honolulu Harbor under present conditions. Keller, Tay, and Collins in 1920 described stagnant and polluted conditions that indicated inadequate tidal and stream-flow flushing. The isocol maps of Metcalf and Eddy in 1944 indicated high bacterial concentration in Honolulu Harbor and also in some parts of Keehi Lagoon. The opening of the Kalihi ship channel from Honolulu Harbor west through Keehi Lagoon to the sea, however, has restored an original but long-closed route for circulation. The currents in the loop around Sand Island seem not to have been investigated.

4.11 Pearl Harbor

Problems of sewage contamination in Pearl Harbor have been noted in several reports (Div. Sewers, 1957b) Div. Sewers, 1958; Austin, Smith, and Assoc. and Metcalf and Eddy, 1962). A survey by Austin, Smith, and Associates (1961a) in Middle Loch off Pearl City, using surface and subsurface floats, indicated the

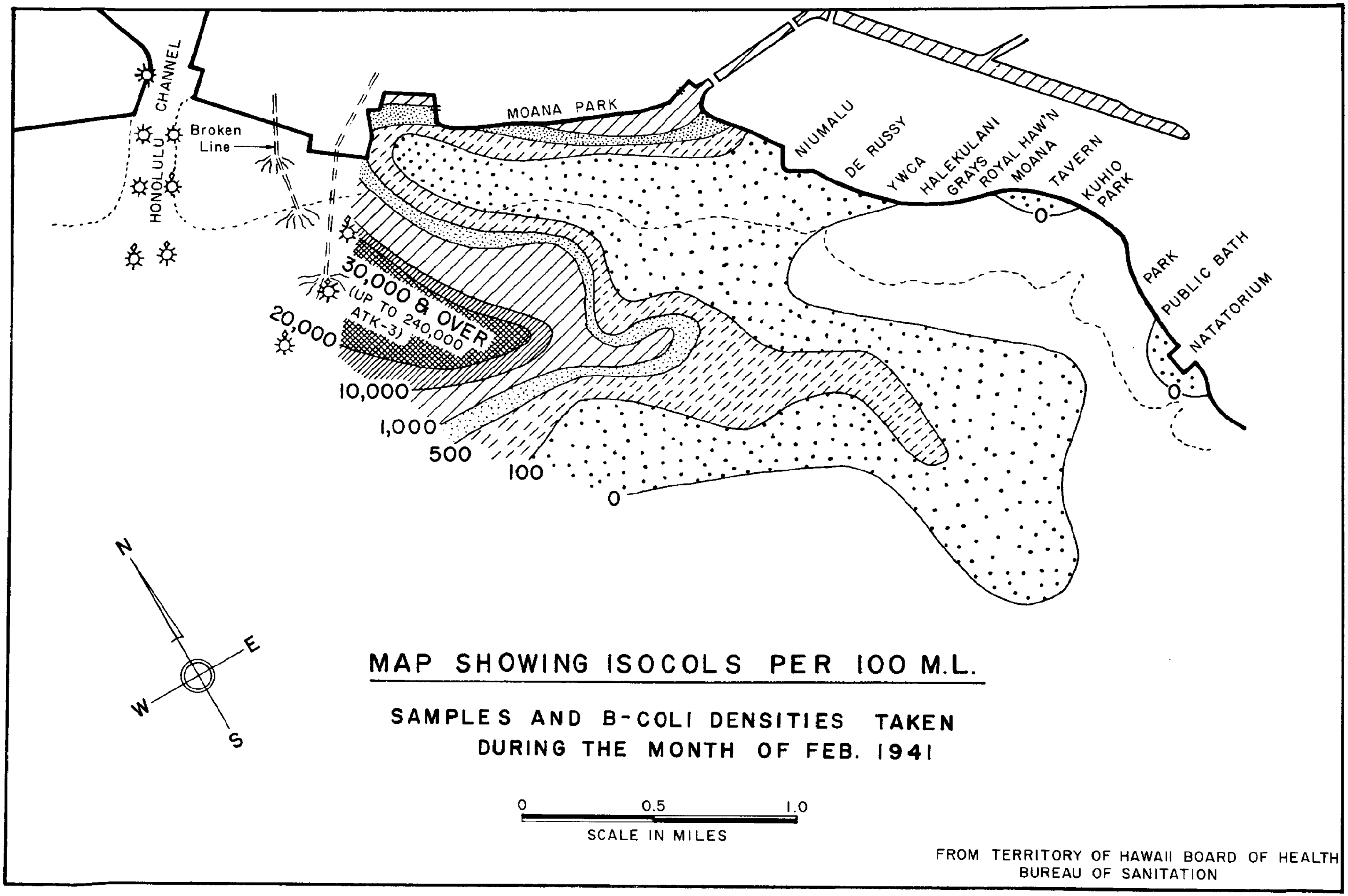


Fig. 33. Coliform concentrations derived from old Kewalo sewer, February 1941 (from Bureau of Sanitation, 1941).

existence of weak but well defined tidal components. The flood, corresponding in phase to the rising tide, set generally northwest toward the head of the Loch, and the ebb, corresponding in phase to the falling tide, generally set southeast toward Ford Island. Superimposed on the tidal oscillations, which involved velocities only on the order of a tenth or tenths of a knot, were a prevailing seaward flow on the surface resulting from stream and spring discharge, and wind drag. The wind affected particularly the surface floats. Presumably similar conditions prevail in other parts of the Harbor.

In another survey made at the harbor entrance by Austin, Smith, and Associates (1960), involving surface and subsurface floats, the flood current was shown entering the harbor with a velocity on the order of 0.2 knot, generally with the tide rise as expected.

4.12 Southwest Coast

Information on currents along the southwest coast of Oahu is derived from:

(a) the Coast and Geodetic Survey (1963a) Roberts current meter study just south of Kaena Point previously referred to;

(b) the Institute of Geophysics drogue studies of 3-4 January 1963 at Kaena Point and 4 miles southeast, previously referred to (Fig.13).

(c) float,drogue, and dye surveys in Pokai Bay and in general off the town of Waianae repeated through most of 1961 by Sunn, Low, Tom, and Hara (1962a)(Figs. 8, 36, 37).

(d) similar surveys southwest of Kaneilio Point in October and November 1961 conducted by Belt, Collins, and Associates (1962b);

(e) remarks by Tippetts, Abbett, McCarthy, and Stratton (1961) concerning currents off Browns Camp;

(f) Institute of Geophysics drogue studies 1 to 2 miles northwest of Barber's Point in April and July 1963 (Fig. 35); and

(g) an Institute of Geophysics paddle-wheel current meter study about $1\frac{1}{2}$ miles northwest of Barber's Point conducted in July 1963 (Fig. 23).

The paddle-wheel current meter data from northwest of Barber's Point (Fig. 23) indicate, for that area, a clear though somewhat complicated tidal behavior, the flood current setting south and the ebb current setting north-northwest. The flood current was more persistent than the ebb current at the time of the measurement, although the opposite should have been expected from the theory discussed in section 2.4. The currents, instead of leading the tides, seem in general to lag behind. The maximum flood current of about 1 knot was associated with the lower of the two high tides, and the ebb tide velocities reached a still higher maximum of about 1.5 knot.

The nearby drogue observations (Figs. 34, 35) agree with the current meter observations as to directions and strength of the currents. They indicate, in addition, that the current strength tends to be considerably greater in the shallow water close to shore than in the deeper water offshore, and that there is a shoreward set in the deeper water during the ebb current not found at the surface. The clockwise swing in current directions observed in the early afternoon of 9 July occurred during a change from flood current to ebb current.

The Tippetts, Abbett, McCarthy, and Stratton notes on currents at Browns Camp are not inconsistent with the above information, but they add nothing to it except that the current speed may occasionally reach 2 knots.

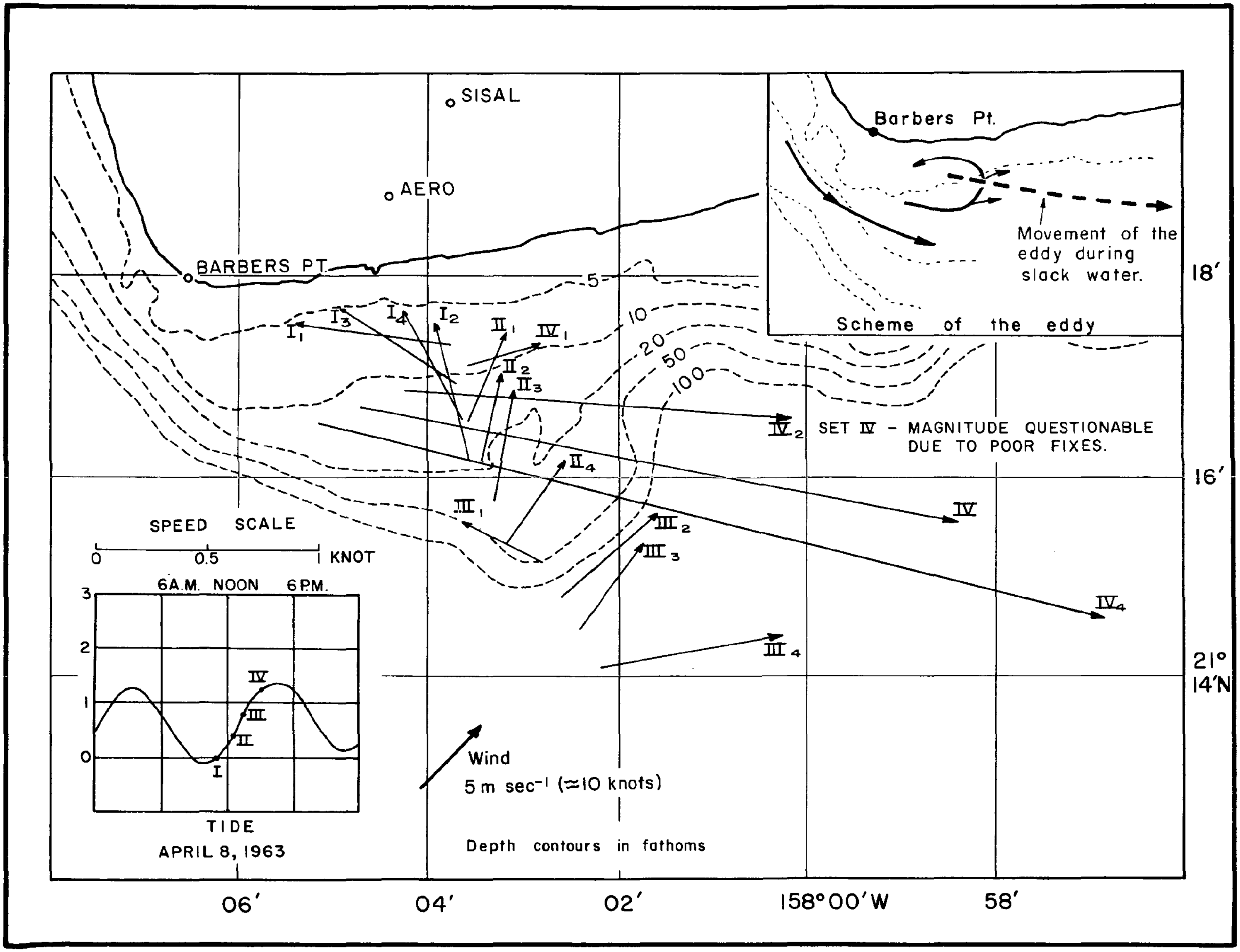


Fig. 34. Results of drogue measurements of currents southeast of Barbers Point, April 8, 1963.

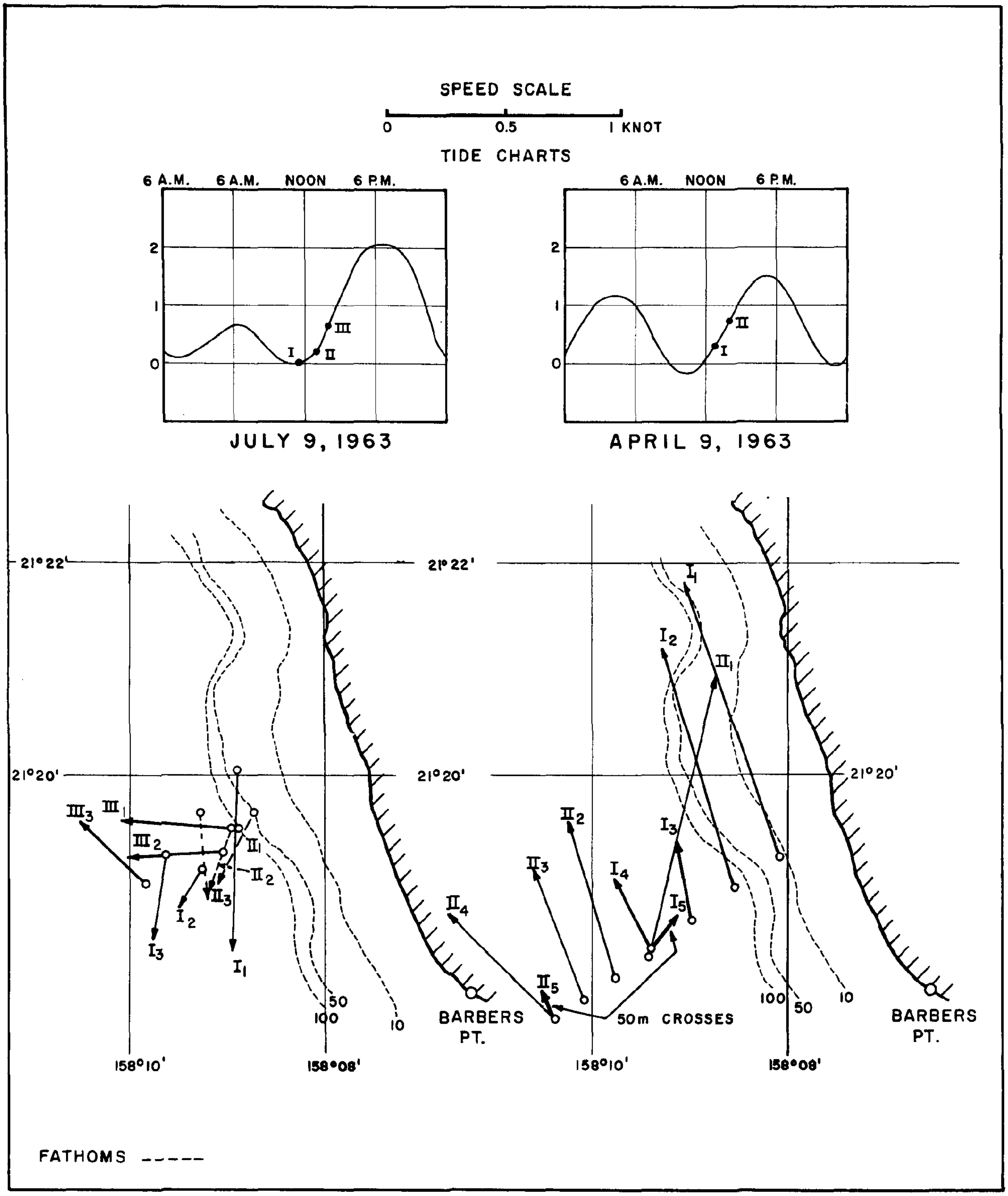


Fig. 35. Results of drogue measurements of currents northwest of Barbers Point on April 9 and July 9, 1963.

The Sunn, Low, Tom, and Hara (1962a) study of the current systems in Pokai Bay and off Waianae was in general a very intensive one, lasting a year and utilizing drift cards, drift bottles, drogues, and dye. Two of the drogue studies were carried through a 24-hour period. Together with the Belt, Collins, and Associates (1962b) study of the currents off Kaneilio Point, it provides an excellent picture of the current system of the area. Off the points the currents are essentially reversing, but generally with the same or a more exaggerated phase anomaly to the tides, as was described from the current meter observations northwest of Barbers Point.

Phase anomalies were found similar to or more exaggerated than those at Barbers Point, currents setting in the direction of the flood occurring sometimes at low tide and currents setting in the ebb direction, at high tide. Inshore, between the points, the currents were more erratic as a result of eddy formation. The generalized patterns of ebb and flood currents found are shown in Figure 36. Trade winds tended to deflect the surface currents seaward and kona winds to deflect them landward resulting in upwelling and anstau conditions.

As previously discussed, the ebb current continues to set northwestward to Kaena Point, whereas the southwestward flood flow along the Waianae coast must stem from a divergence about 2 miles south of the Point.

4.13 Summary of Coastal Currents Around Oahu

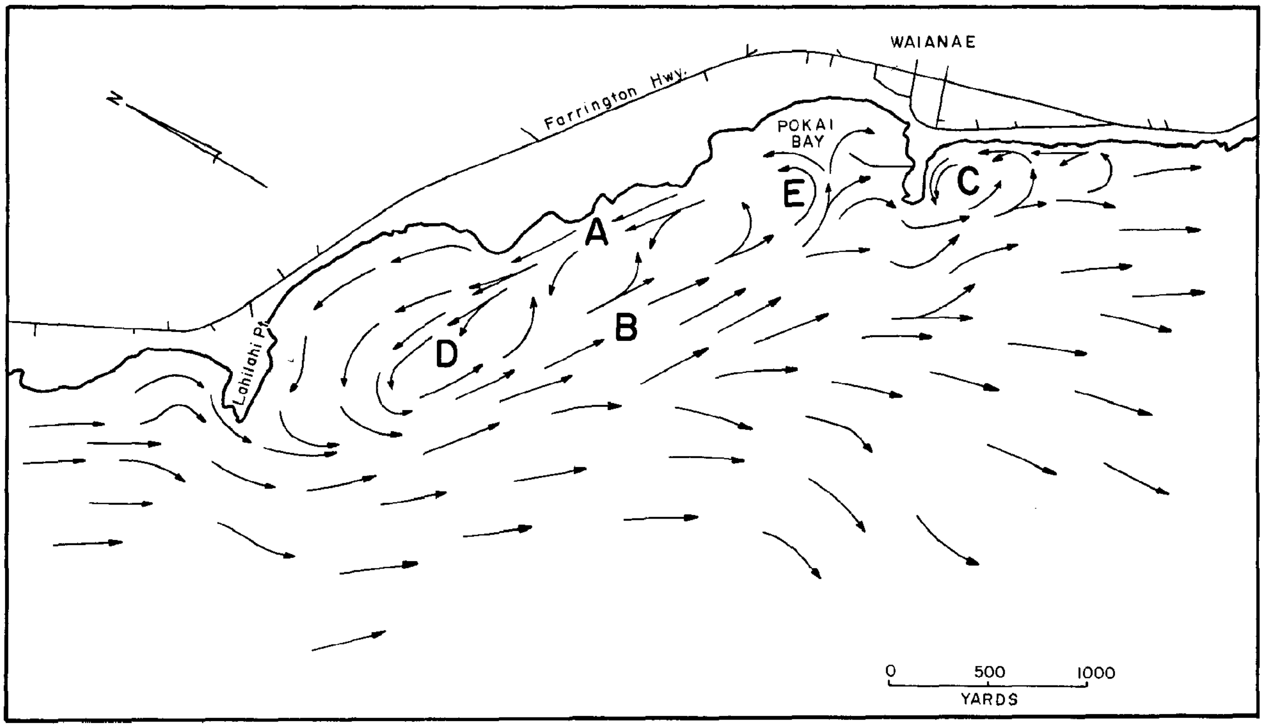
The coastal currents around Oahu are apparently consistent in general with the pattern expected from the distortion by the island of a current while results from the superposition of a tidal current on a permanent flow. The irregular shape of the island introduces considerable irregularities into the pattern, and a few features of the currents do not easily fit with the pattern expected.

The flood current apparently impinges on the island and diverges generally at Makapuu Point or in the vicinity of Waimanalo, but possibly on occasion as far northwest as Ulupau Head. It appears to converge somewhere in the western part of Mamala Bay. The ebb current diverges somewhere off Mamala Bay, probably off the western part and appears to have a main reconvergence at Kahuku Point. Currents set almost continuously northwesterly along the northeast coast and perhaps not quite so continuously in the vicinity of Waimanalo consistent with expectations for the coastline between the flood divergence and the ebb convergence. The currents also set almost continuously westward past Kaena Point, as the result perhaps of eddying around the point. Along other shores they generally reverse with the tides, but one direction frequently predominates over the other.

In the bays and at other irregularities in the shoreline eddies are formed. In some areas of Mamala Bay the current patterns are especially irregular as the result of eddying and also of the relative weakness of the tidal currents compared with wind drag and mass transport. In the shallow water near Sand Island the currents sometimes set for several days in one direction, then reverse.

Pearl Harbor shows the typical tidal circulation of a deep bay with a narrow entrance. Reef and lagoon circulation is notable at Kaneohe Bay and Ala Moana.

Figure 37 shows diagrammatically the general pattern of the ebb currents around Oahu during the trade-wind season. In interpreting this diagram several points must be kept in mind. First, the degree of generalization is somewhat variable from place to place. In some areas, particularly the area of east-west divergence in Mamala Bay there are likely to be several



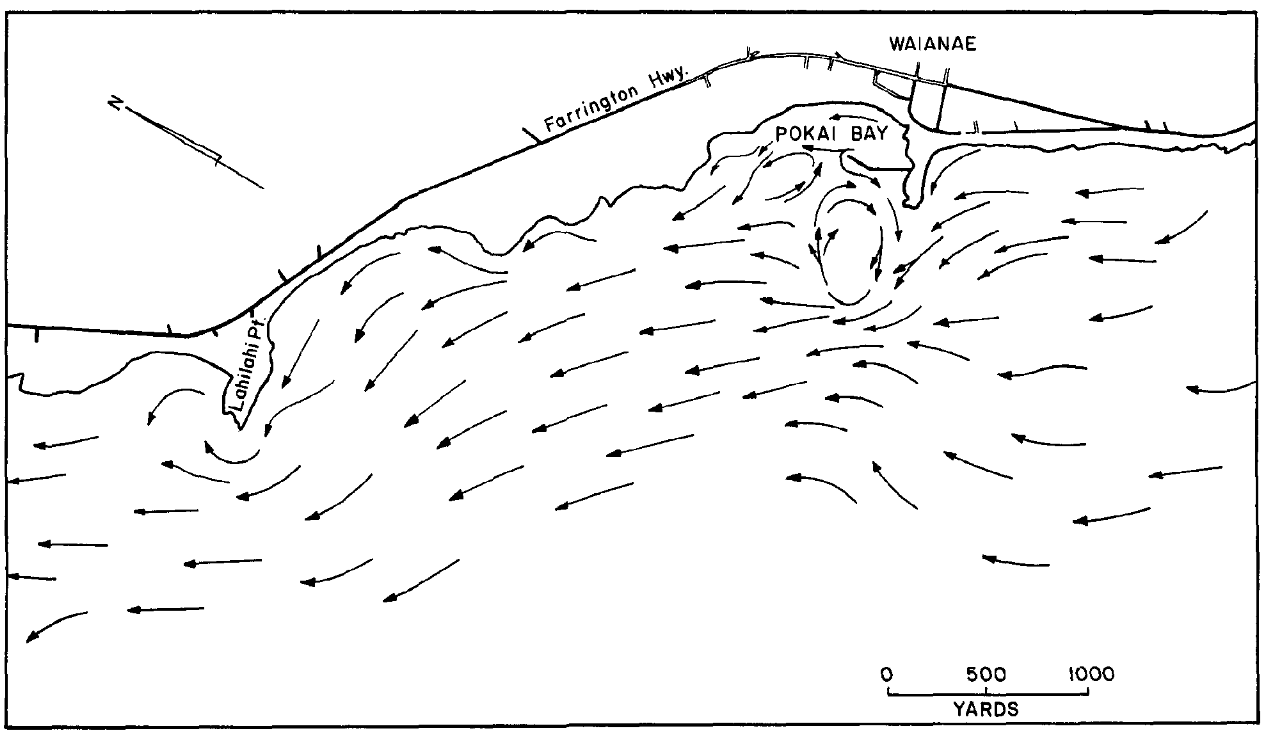


Fig. 36. Generalized flood (top) and ebb (bottom) current patterns for Waianae area (from Sunn, Low, Tom, and Hara, 1962).

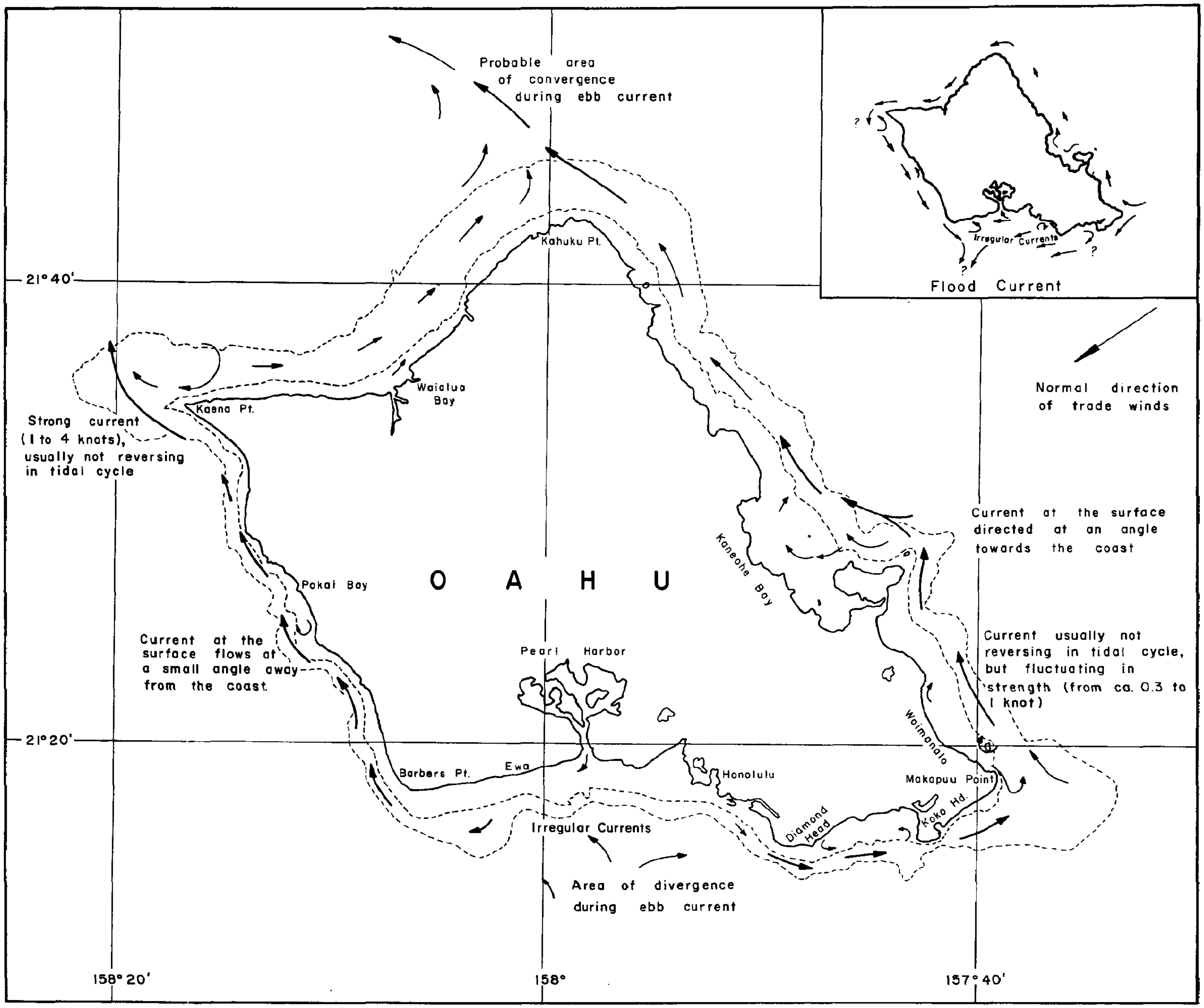


Fig. 37. Generalized ebb current pattern around Oahu during trade wind season. Inset shows generalized flood current pattern.

zones of slope (north-south) convergence and many eddies whose positions are not predictable, whereas in other areas the predicted prevailing current may be expected to be strong and regular. Second, the chart should not be regarded as a strictly synoptic one because the tide phases vary somewhat in time from place to place, in general being about an hour earlier on the north coast than on the south coast. The inset shows diagrammatically the general pattern of the flood currents during the trade wind season.

The pattern during kona weather is less well outlined, but apparently the main differences are in the wind effects on the surface currents. Although there may be changes due to the seasonal shifts in the permanent drift, these have not been identifiable. In any case they are likely to be less pronounced than the random changes in the permanent drift, and they are certainly less pronounced than the tidal changes.

5. COASTAL CURRENTS AROUND MOLOKAI, LANAI, KAHOOLAWE, AND MAUI

5.1 Molokai

According to the Coast Pilot (Coast and Geodetic Survey, 1963a) currents are reported to set westward along the entire northern coast of Molokai, but there seem to have been no reliable observations.

Again according to the Coast Pilot: "Current observations have been made at several places along the southern shore of Molokai between Kamalo and Laau Point. They indicate, in general, an eastward flow along the shore in the vicinity of Kaunakakai and Kamalo [with a velocity of about 1 knot off Kamalo], and a westward flow near Laau Point. Combined with these movements are tidal currents [with the flood setting west and the ebb setting east] . . . The westward flow near Laau Point is reported to turn sharply northward at the point . . . " A current rip often observed off Laau Point is probably the result of the convergence of the northwesterly current rounding the point and a southerly current following the west coast. Currents are said to set northeastward along the southeast coast. Coast and Geodetic Survey (1963b) observations in the Kalohi Channel in 1961 show reversing currents, the flood current with an average maximum velocity of 0.4 knot setting west-southwest and the ebb current with an average maximum velocity of 0.5 knot setting east-northeast.

5.2 Lanai

No reliable current measurements have been made around Lanai except those in the Kalohi Channel, discussed in section 5.1, and those in the

Auau Channel, discussed in section 5.4. It seems probably that the flood tide current diverging off the northeast coast of Lanai converges again off the southwest coast, and that the ebb tide current shows the opposite relationship. However, the tidal currents should be weaker on the southwest side becuase of the lack of constriction in the narrow channels, and the permanent west or northwest drift may predominate.

5.3 Kahoolawe

According to the Coast Pilot the prevailing current is westerly along the south coast of Kahoolawe, swinging to northwesterly at the westerly tip of the island. The currents in the Kealaikahiki Channel were found by Coast and Geodetic Survey (1963a) measurements in 1962 to be weak and variable and influenced by the wind. The maximum velocity observed was 0.5 knot in a generally northeast direction. One may suspect that systematic tidal currents could be found by careful analysis As previously described, the currents in the Alalakeiki Channel are variable, but the prevailing drift on the Kahoolawe coast is southeasterly.

5.4 West Maui

According to the Coast Pilot (Coast and Geodetic Survey, 1963a): "The current at Lahaina usually sets northward and reaches a maximum velocity of 1 or 2 knots before low water. Before high water the current is normally quite weak and may set either northward or southward." A confused current setting generally southward is reported at Mala, only a mile north of Lahaina. Still farther north at Kekaa Point reversing north and south tidal currents of 0.5 knot strength have been measured. The phase relations are not stated. Offshore in the Auau Channel tidal currents were measured by the Coast and Geodetic Survey in 1962. The flood current, with an average maximum velocity of 0.6 knot, sets east, and the ebb current, with an average maximum velocity of 0.5 knot, sets west (Coast and Geodetic Survey, 1963b). In the Pailolo Channel, farther north, weak, variable currents with a maximum velocity of 0.6 knot were measured in the same season. It seems probably from these rather meager and somewhat inconsistent data that (a) the dominant systematic currents along the west coast of West Maui, as well as in the channels between Maui and Lanai and Molokai, are tidal in nature, with the flood current setting generally southwest in the Pailolo Channel, west in the Kalohi Channel, and southeast in the Auau Channel; (b) these tidal currents, except in the middle of the Auau Channel, are sufficiently weak for wind or other random effects to complicate the general pattern; and (c) the pattern, close to shore, is complicated by topographic effects. Northerly currents are reported off Napili Bay by the Coast Pilot, but no reliable current measurements seem to have been made along the north coast of Maui from Kekaa Point to Kahului Bay.

5.5 Kahului Bay and Harbor

An intensive study of the current systems in Kahului Harbor and in the bay just outside was conducted in August and September 1962 by Herschler and Randolph (1962) using surface and subsurface drogues, lath floats, drift bottles, drift cards, and dye. All measurements were made during daylight hours in tradewind weather. The floats and especially the cards and drogues were found to be affected directly by the wind, and almost all of the apparent sets both inside and outside the harbor were west or southwest, parallel to the wind. The dye studies showed tidal currents reversing near the harbor mouth and in the harbor, the flood currents entering and the ebb current leaving the harbor, each with maximum velocities of about 0.3 knot (Fig. 38). Outside the harbor the dye studies showed a continuous westward drift past the entrance with an average velocity of about 0.2 knot and no tidal reversal. This drift turned northwest just west of the entrance, leaving room for an eddy in the vicinity of the Wailuku sewer outfall west of the harbor.

Upwelling outside the east breakwater was shown on a rising tide by chloride content greater than normal. The chloride content of the surface water in the harbor was progressively lower closer to shore as a result of ground-water discharge. The dissolved oxygen content and biological oxygen demand of the water in the harbor indicated efficient flushing by the tidal currents.

5.6 North Coast of East Maui

An eastward current has been reported off Pauwela Point and a northeastward current off Nahiku by the Coast Pilot. It seems very unlikely that these reports indicate the prevailing current direction, and there seem to have been no reliable current observations between Kahului and Hana.

5.7 South Coast

The reversing currents in the Alenuihaha Channel are described in section 6.1. Near the south Maui coast, the dominance of the tidal components is pronounced. At Kauiki Head, to the east, the Coast and Geodetic Survey (1963a) has measured the south-setting flood current with a velocity of 1 knot, and according to the Coast Pilot, the north-setting ebb current has a velocity of 1.5 knots. Near Alau Island the tidal

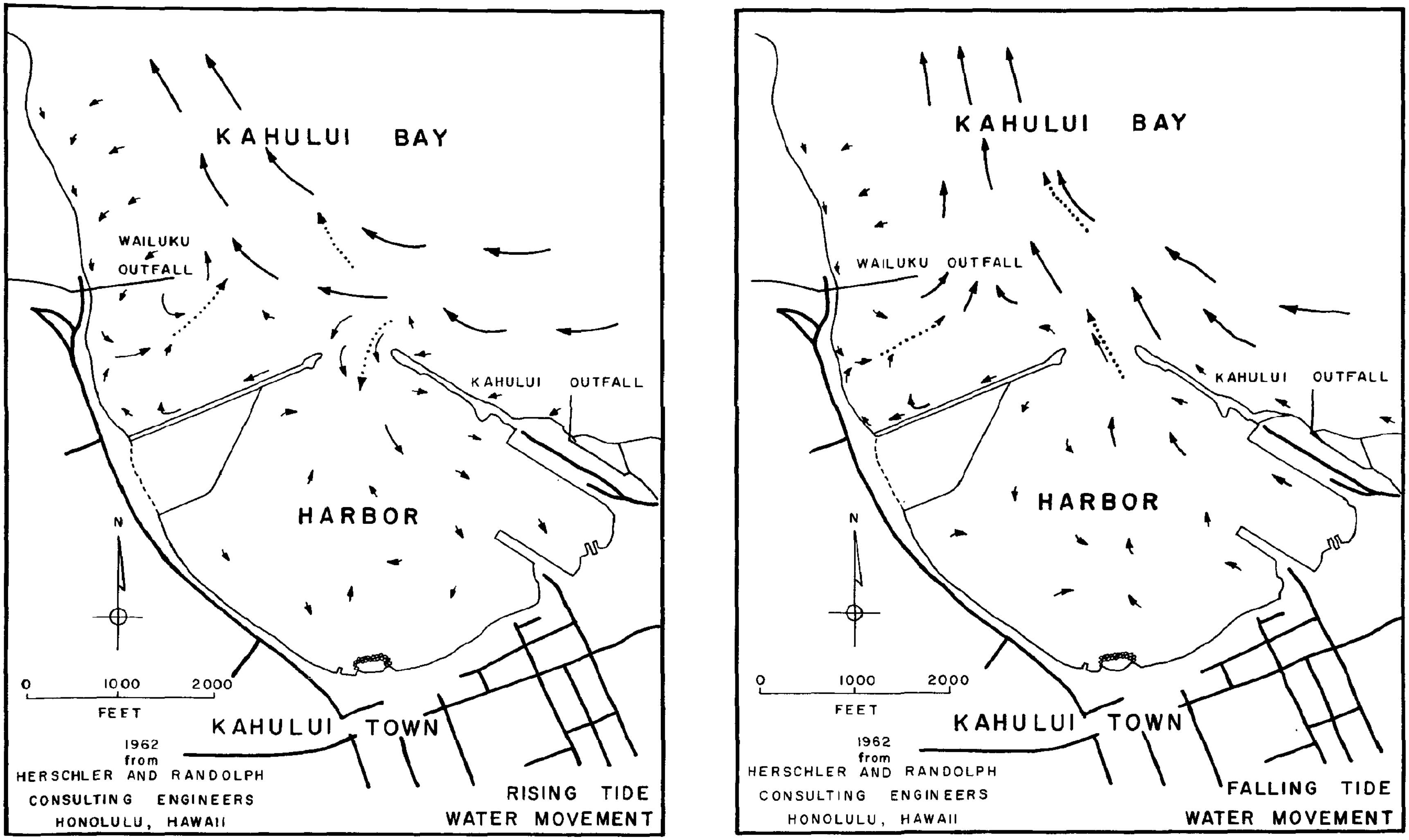


Fig. 38. Generalized flood (left) and ebb (right) current patterns for Kahului area (from Herschler and Randolph, 1962).

currents have velocities of 0.5 knot, and there is said to be an eddy between the Island and Kauiki Head. Tidal currents of as much as 0.8 knot have been observed 1 mile southeast of Cape Hanamanioa (Coast and Geodetic Survey, 1963a), but the phase relations are uncertain.

5.8 Alalakeiki Channel

Coast and Geodetic Survey (1963a) observations in 1962 show the current in the Alalakeiki Channel to be variable, probably as a result of tidal effects, with maximum velocities of 1 knot, and with a general net northwesterly drift of 0.5 knot along the Maui shore.

5.9 Southwest Coast

A northwestward current has been reported in Maalaea Bay (Coast and Geodetic Survey, 1963a) but no reliable current observations seem to have been made anywhere along the southwest coast of Maui from Makena to Lahaina.

5.10 Summary of Coastal Currents Around Islands of the Maui Group

Because of the shallow water connecting them, Molokai, Lanai, Kahoolawe, and Maui probably act somewhat as a unit in diverting the permanent flow and tidal currents. It seems best therefore to summarize together the currents around these islands of the Maui group. The available coastal current data is shown in simplified diagrammatic form in Figure 39, together with some speculative interpretations of current directions shown with question marks.

On the basis of the theory discussed in section 2.5, it seems probable that the principal flood current divergence is near the eastern point of Maui, although the report of easterly currents along the northeast coast of East Maui may indicate that the divergence moves sometimes to the north point of East Maui. Supplementary areas of flood divergence must be located near the east end of Molokai, the northeast point of Lanai, and the east point of Kahoolawe. Flood convergences are probably located somewhere in the vicinity of Olowalu, Maui, off the southwest points of Kahoolawe and Lanai, and off Laau Point, the southwestern point of Molokai. The principal convergence may be in any of the last three areas, but seems most likely to be off Laau Point.

The principal ebb divergence is probably off the south point of Kahoolawe. Subsidiary divergences are probably located in Maalaea Bay, Maui, off the south coast of Lanai, and somewhere between Laau Point and Kaunakakai, Molokai. The principal ebb convergence is probably off the northeast tip of Molokai, and subsidiary convergences off the north point of West Maui, the northeast point of Lanai, and the east point of Kahoolawe.

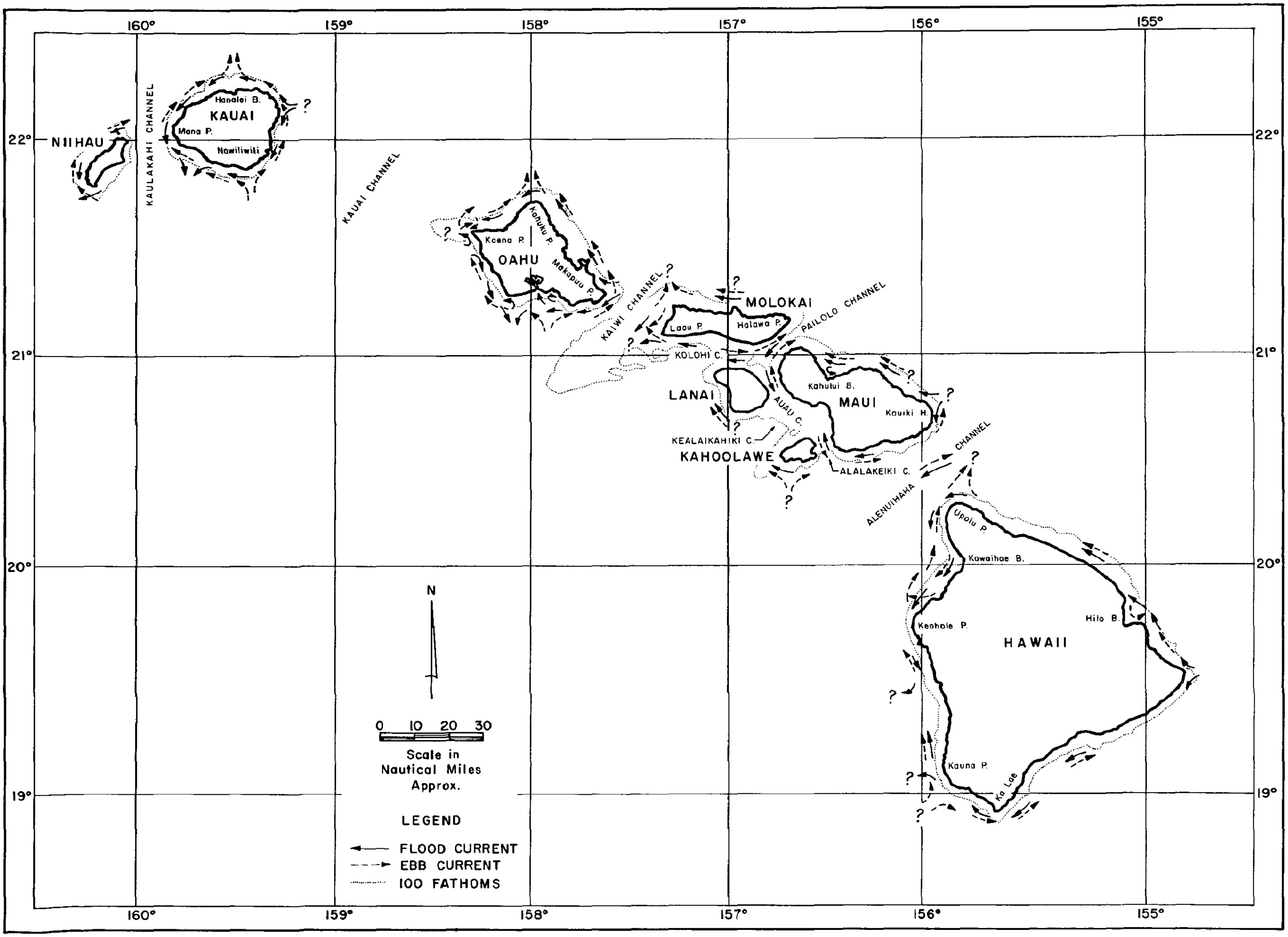


Fig. 39. Generalized diagram of coastal currents around the Hawaiian Islands.

6. COASTAL CURRENTS AROUND HAWAII

6.1 Alenuihaha Channel

According to the Coast Pilot (Coast and Geodetic Survey, 1963a): "During strong trade winds the [Alenuihaha] channel is quite rough and a current of 1 to 2 knots sets westward, but during the calms which frequently follow, there is at times an easterly set of about 1 knot, and during kona winds the easterly set may reach a velocity of 2 or 3 knots." It seems probable that these observations pertain strictly only to the surface layers most affected by wind drift. At depth, the reversibility is probably a function not only of wind direction and speed but of tide phase, the flood current vector setting southwest and the ebb current vector setting northeast.

6.2 Northeast Coast

Along the northeast coast of Hawaii from Cape Kumukahi, the eastern extremity, to Upolu Point, the northern extremity, the current sets generally to the northwest, according to the Coast Pilot. However, as noted by Belt, Collins, and Associates (1961a) muddy water from the sugar mills along the Hilo Coast may frequently be seen moving southward. It seems possible that at some times the permanent flow follows the coast into Hilo Bay but at other times diverges from the coast at Leleiwi Point, permitting an eddy or tidal effects to cause a reversal in Hilo Bay. The direction and strength of the trade winds may be influential in determining the current direction in the outer part of Hilo Bay.

6.3 Hilo Harbor

Currents within Hilo Harbor, as shown by two surveys in January and April 1961, consist of a reversing component setting into and out of the harbor, superimposed upon a net drift out of the harbor resulting from the discharge of the Wailuku and Wailoa Rivers (Belt, Collins, and Assoc., 1961a). Velocities are not directly indicated in the report on the surveys but appear to be less than 0.1 knot below the surface, as indicated by the trajectories of dye patches. Subsurface drogues and especially surface floats showed longer trajectories apparently influenced by the wind as well as by the more rapid outflow of the fresher water at the surface. A dye patch outside of the entrance drifted to the northwest, at less than 0.1 knot, showing no digression toward the entrance on a rising tide. According to the Coast Pilot a north-northwest setting current of as much as 1 knot has been reported in the approach to the harbor, probably when the rivers are in flood.

The Belt-Collins study found pollution and stagnation in the harbor indicated by both chemical and bacteriological conditions.

6.4 Southeast Coast

According to the Coast Pilot, the current sets generally to the southwest along the southeast coast from Cape Kumukahi to Ka Lae, the southern extremity of the Island. However, also according to the Coast Pilot, there is an inshore counter current passing around Ka Lae in the reverse direction and traceable as far as Keauhou Point. It seems probable that these observations indicate, in reality, a reversal with time rather than a reversal with position, the stronger southwesterly current resulting from the reinforcement of the permanent flow by a tidal current during the flood and by the prevailing tradewind drift, a weaker reversed current resulting at the ebb.

6.5 Southwest Coast

The configuration of Ka Lae suggests that an eddy may be formed in its lee during the flood, so that the current sets generally east-southeast. The Coast Pilot in fact describes an inshore, southeast-setting counter current along the coast from Ka Lae to Kauna Point. From Kauna Point to Keahole Point the current usually sets to the north-northwest. Velocities approaching 2 knots have been reported in the vicinity of Milolii, according to the Coast Pilot.

6.6 Kailua-Kona

Float observations off Kailua-Kona by the Department of Health in May 1961 (H.A.R. Austin and Assoc., 1961) appear to confirm the generally northwest set there. The floats used were obviously greatly influenced by winds, and showed reversing trajectories that are probably almost entirely the result of the sea breeze-land breeze wind pattern characteristic of the area. There is some suggestion of the existence of a south-setting component, or at least a slackening of the northwest current, with the rising tide, but if so the tidal current is in phase with the current expectable west of Upolu Point rather than the current expectable west of Ka Lae. Austin, Smith, and Associates point out that the sea-breeze would drive floatables on shore at Kailua-Kona.

6.7 Northwest Coast

Current rips are frequently reported north of Keahole Point, according to the Coast Pilot; a 0.5 knot southwesterly current has been observed at Kiholo Bay; and there is practically no current at Kawaihae. These observations suggest that the northerly current following the coast south of Keahole Point sets offshore from the coast north of that Point, leaving room for a south-setting eddy inshore. There are persistent reports of a constant north-setting current off Mahukona, converging off Upolu Point with the northwest-setting current following the northeast coast of the Island. However, Coast and Geodetic Survey measurements off Mahukona showed both north- and south-setting currents with velocities of nearly 1 knot. It seems probable that these reversing currents are tidal, the south set representing the flood and the north set the ebb, and that the divergence between the normal north set at Upolu and the normal south set in Kawaihae Bay shifts north and south of Mahukona with the tide stage.

6.8 Summary of Coastal Currents Around Hawaii

The available data on coastal currents around Hawaii, although meager, suggest that the major flood divergence on the island is off Cape Kumukahi. The location of the major flood convergence is uncertain and may be anywhere from Kauna Point to Kailua-Kona. The major ebb divergence is probably off Kauna Point, and the major ebb convergence is probably off Upolu Point. There appears to be a large ebb counter-current in the vicinity of Kawaihae, and there may be a counter current at any tide stage in Hilo Bay. The available current information and additional interpretation are diagrammed in Figure 39.

7. SOME CHEMICAL, BIOLOGICAL, AND GEOLOGICAL OBSERVATIONS PERTAINING TO SEWAGE DISPOSAL

7.1 Distribution of Chemical Properties off Sand Island Sewer and in Kaneohe Bay

The distributions of chlorinity, dissolved oxygen, and phosphates were measured off the Sand Island sewer outfall in August 1962. The results, shown in Appendix Table 5a and plotted in Figure 40, indicate that most of the sewage is confined to a relatively thin surface layer, the thickness of which increases slightly with distance from the source. The oxygen and phosphate values suggest that the breakdown of organic matter is relatively slow close to the source but speeds up farther away. Intensive phytoplankton growth has been noticed at a distance from the outfall, presumably resulting from the supply of nutrients from the sewage to the originally relatively nutrient-poor oceanic waters.

Some additional chemical studies were carried out in Kaneohe Bay in September 1962 to ascertain whether any stagnation of deep water occurs there. The results are shown in Appendix Table 5a. A slight stagnation of the deeper waters in the southeastern part of the Bay can be noticed with respect to sewage disposal in these waters. The water exchange and flushing of this part of the Bay are slow and the sewage is carried by surface wind-driven currents toward the Kaneohe shore. Continued attention should be given to the conditions in this part of the Bay, although the values are not alarming at present.

7.2 Bottom Deposits off Sand Island Sewer

An intensive sampling of bottom deposits was made off the Sand Island sewer outfall to a distance of about 1 mile. Bare areas of old coral and other consolidated calcareous rocks were common, and where there was a mantle of unconsolidated sediment, it was usually coral sand. No organic or directly polluted sediments were found. The sampling indicated vigorous biological growth on the bottom, especially downslope about one-half mile from the shore where there were large colonies of mussels. The relatively richer biological growth on the bottom suggests that the sewage has a fertilizing influence. No direct effects of sewage on coral growth or its breakdown were observed. There were no living corals in the area investigated, and the pieces of coral brought up from the bottom did not indicate any acceleration of breakdown.

7.3 Bacterial Die-off in the Sea

It has been universally found that bacterial concentrations in sea water polluted with sewage are lower than can be accounted for by dilution alone. The extra decrease in concentration has been variously attributed to the activity of bactericidal agents in the sea water, bacteriophages, or protozoans, to adsorption on sedimentary particles followed by sedimentation, or to the effects of solar radiation. Various bacteria have been found to be differentially resistant, but prior to 1959 the studies on bacterial die-off in sea water had been done only in the laboratory or, if in the sea, with dialysis tubes and laboratory cultures. The results were therefore quantitatively suspect, and in any case could not have been expected to pertain closely to conditions in Hawaiian waters.

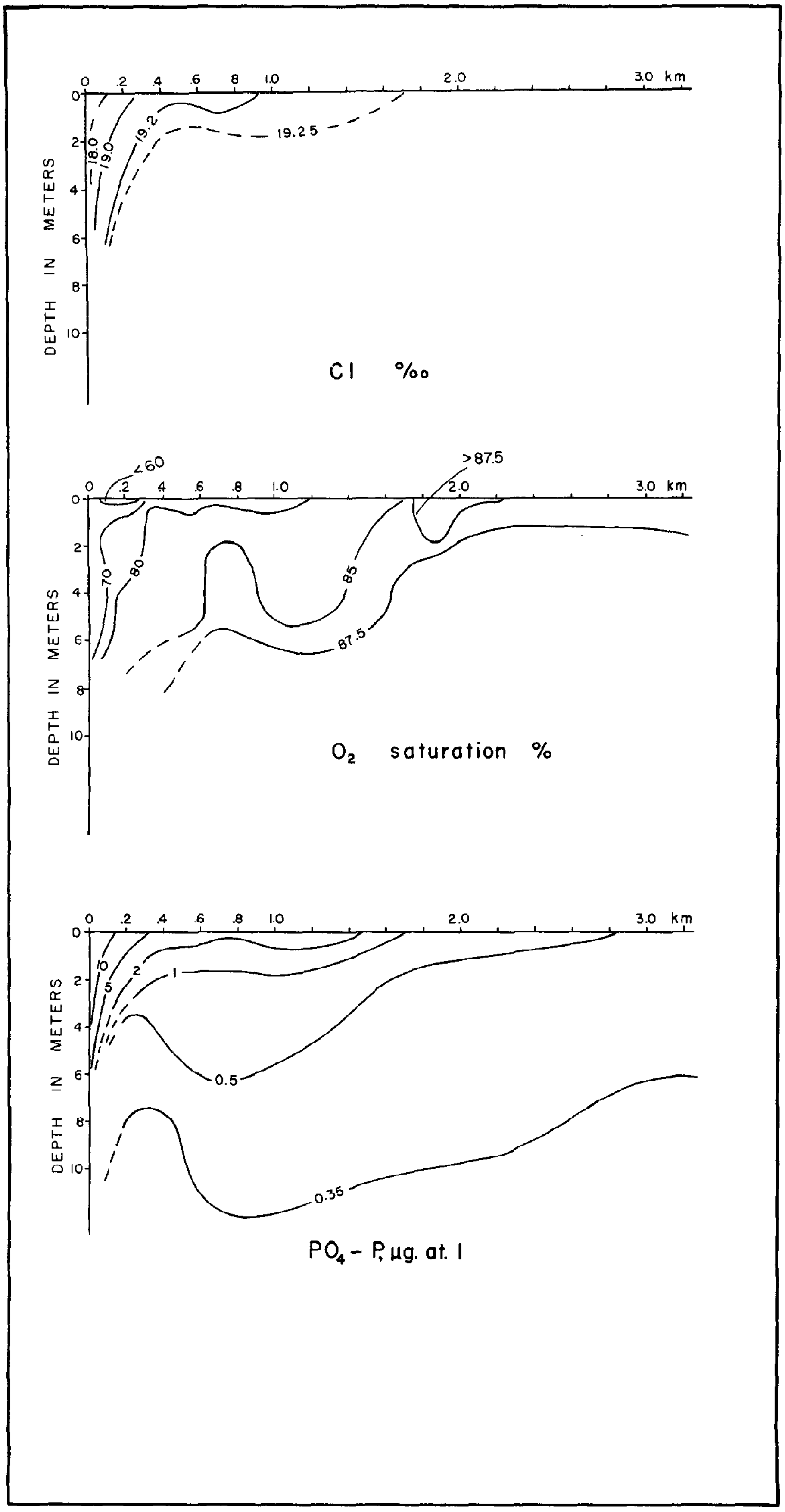


Fig. 40. Distribution of chlorinity, dissolved oxygen, and phosphates off the Sand Island sewer outfall.

A special study of the survival of sewage bacteria in the sea was made by Iha in connection with the Holmes and Narver and Belt, Collins, and Associates (1959a) study of sewage disposal possibilities in Kailua Bay (Iha, 1960). Actual sewage, dosed with a radioactive tracer and a dye tracer, was introduced into the bay on five occasions, one each in the months from April through September 1959. The movement of the dispersing cloud of sewage was tracked visually by means of the dye. A sample was taken within a few minutes of the initial introduction and additional samples were taken at intervals thereafter through periods ranging from 40 to 116 minutes. The dilution of the sample was measured by the decrease in radioactivity. Concentrations of both coliform bacteria and enterococci were measured by standard techniques.

The decreasing concentrations of both coliform bacteria and enterococci, even after corrections for dilution, showed less than 0.01 per cent survival after 30 minutes. Sedimentation was found to be insignificant and bactericidal action of the sea water was judged predominantly responsible for the die-off. The survival rate for the enterococci was found to be higher than that for the coliform bacteria.

Iha's results were not expressed in terms that are directly usable for computations of bacterial die-off in practical sewage disposal problems. Bacterial die-off has been expressed by previous investigators in several ways, reducible to the following forms:

$$\frac{C_B}{C_{B_o}} \cdot \frac{1}{D} = X^{k''} \quad \text{(Conway, date?)}$$

$$= \exp(-k'T) \quad \text{(Chick, 1908; Brooks, 1960)}$$

$= \exp\left[-k\,(t - to)\right]$ (Ketchum and others, 1949; Vaccavo and others, 1950)

where C_B = concentration of bacteria

C_{B_o} = initial concentration of bacteria

D = dilution factor

X = distance from point of injection

t = time elapsed from injection

t_o = lag

k, k', k'' = constants

Iha's results have been plotted in Figure 41 in terms of the natural log of the bacterial concentration ratios, allowing for dilution. To these data linear regression lines have been fitted by least squares. The results fit the form:

$$\frac{C_B}{C_{Bo}} \cdot \frac{C_{To}}{C_T} = \exp\left[-k\,(t - t_o)\right]$$

where: C_T = concentration of tracer

C_{T_o} = initial concentration of tracer

and the constants are:

	Coliform bacteria	Enterococci
k	9.76×10^{-3}	2.15×10^{-3}
t_o	-72 min.	-308 min.

It will be noted that initial rates of decline in bacterial concentration in Iha's experiments were more rapid than subsequent rates. The apparent negative values for the lag, t_o, are a consequence. The reasons for this behavior are not apparent, and the values of t_o are, perhaps, open

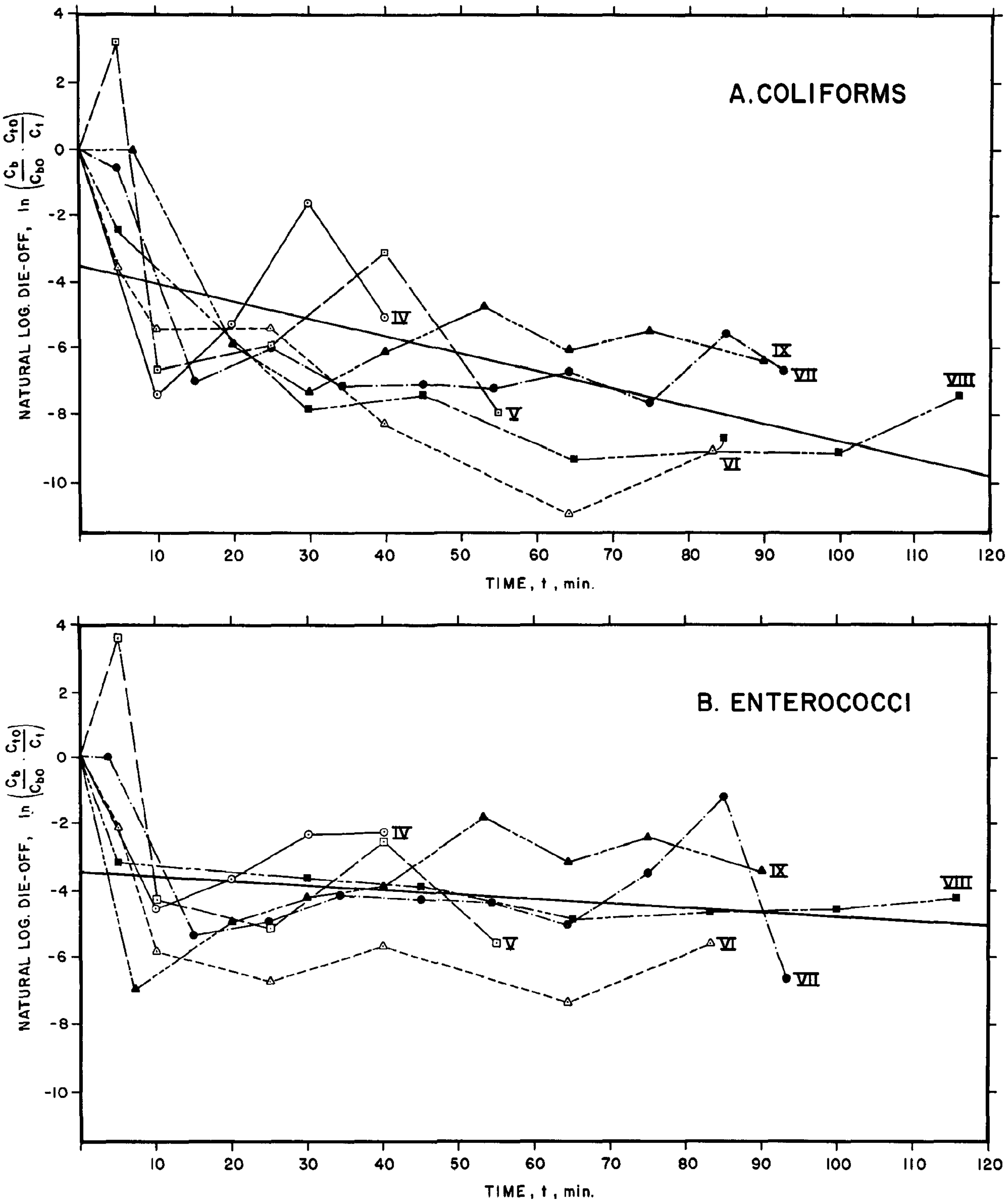


Fig. 41. Bacterial die-off in sewage disposed off in the ocean. (Computed from data of Iha, 1960.)

Roman numbers indicate months of experimental runs.

C_B = concentration of bacteria

C_{B_o} = initial concentration of bacteria

C_T = concentration of tracer

C_{T_o} = initial concentration of tracer to question. Certainly a curvilinear relationship would fit the data better than the linear relationship used, but the significance of the improvement in fit would be questionable. It seems probable, however, that the values of k are reasonably accurate for Kailua conditions, and certainly the over-all relationships are the best that are available for Hawaiian conditions in general.

7.4 Biological Oxygen Demand of Sea Water

A special study of the biological oxygen demand (BOD) of sea water has been carried out by Laevastu, Zeitlin, and Song (ms). With respect to sewage disposal the main results of this study, which will be published in a separate report, are that the routine methods of BOD determination, as used with fresh water, are of questionable value in marine waters. The oxygen consumption of sea water depends on numerous factors but is largely a function of the ratio of solid surfaces and does not indicate directly the degree of pollution or the power of self-purification. A method of BOD determination involving filtration of the sea water after collection, the use of standardized sample bottles, and the use of standardized incubation conditions is recommended.

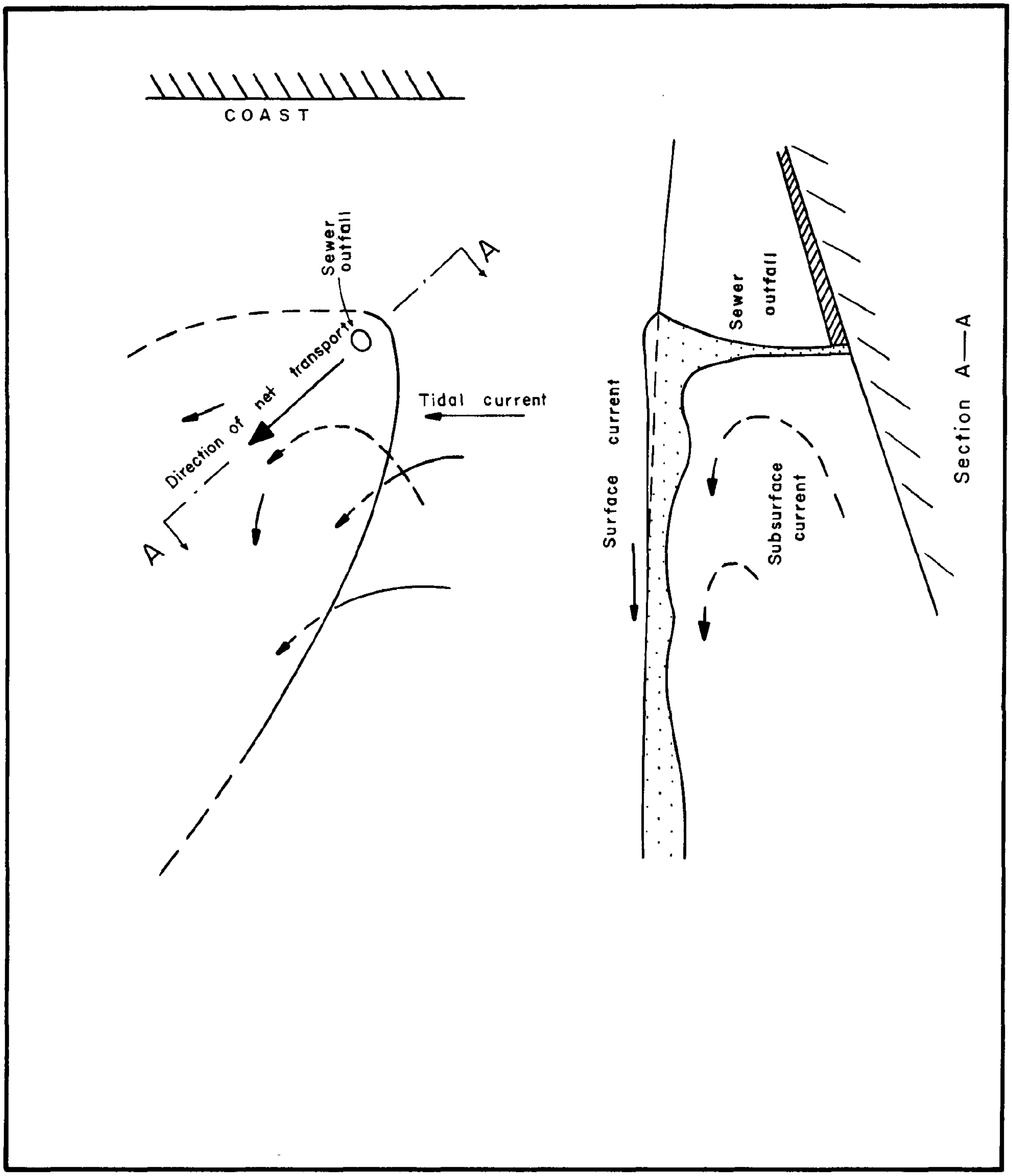


Fig. 42. Schematic circulation at the outfall of a sewer.

8. APPLICATION OF COASTAL CURRENT AND RELATED INFORMATION TO SEWAGE DISPOSAL PROBLEMS IN COASTAL WATERS

It is the aim in disposing of sewage into natural waters that the sewage be decomposed and dispersed in as short a time and distance as possible, and particularly before the waters reach any shoreline or other region where the sewage can be deleterious. In this discussion of means to approach problems of sewage disposal at sea, the processes of dispersal and decomposition will be discussed first, then methods of analysis using coastal current data and other related information.

8.1 Processes of Dispersal and Decomposition of Sewage at Sea

When fresh sewage is introduced into the sea from an outfall on the bottom, the sewage rises to the surface because of its lower density, diffusing on the way up because of the turbulence induced by its own motion. The diffusion may be promoted by injecting the sewage horizontally through a "diffuser" having several outlets. At the surface the sewage forms a semi-discrete body floating on and displacing the salt water. Within this body there is a radial spread from the point of its emergence under the influence of any residual head undissipated in the jets rising to the surface. Eddy diffusion associated with the turbulence of the ocean waters mixes the sewage with the flanking and underlying salt water. The concentration of sewage in the body decreases, its salinity increases, and its boundaries gradually disappear. The ocean current provides the continuous supply of sea water into which the sewage can be mixed, and carries away the diluted sewage. A convective circulation is also set up to replace the sea water mixed into the sewage Figure 42 shows diagrammatically the circulation pattern established at a sewer outlet.

The currents transport the continuously expanding and diluting cloud of sewage away from the area of its injection. Variations in current direction and strength complicate the picture, of course. In a rapidly moving current the initial dilution may be great, whereas in a sluggish current the sewage may remain relatively concentrated. With a tidal current reversal, sewage that is born away from the sewer outlet and diluted can later be carried back over the outlet and thus receive an additional dose of pollution. Mass transport and particularly wind drag may cause the surface and submerged parts of the sewage cloud to move in different directions The wind may drive any floatables in a direction quite unlike that taken by the suspended matter and the floatables may be re-concentrated and transported in a concentrated state in a surface convergence.

The continuing dispersal of the sewage is largely the result of turbulent mixing which is generated in several ways and on several scales. On the largest scale is the eddying resulting from the instability of the major ocean currents. This major eddying and the orbital motion associated with the tides lead to shearing which is responsible for eddying on a smaller scale. Large-scale eddies are generated as the currents move past islands; smaller scale eddies, as they move past irregularities in the coastline or over irregularities in the bottom. Still smaller scale eddies result from the shearing of the surface waters over deeper waters, as with wind-driven currents and mass transport. Regardless of the initial scale of the eddying, the larger eddies break down to smaller ones with shorter characteristic periods. Recordings of currents by paddle-wheel current meters (Figs. 10, 17 through 23) or by Ekman current meters (Appendix Figs. 5 and 6) always show evidences of moderate-period turbulent fluctuations of current speeds and directions. Shorter period fluctuations invariably present cannot be recorded except by instruments having rapid responses.

The biochemical processes involved in the decomposition of sewage in sea water are certainly at least as complicated as the physical processes of transport and dispersal of the sewage, and can be no more than briefly summarized here. Depending on the oxygen availability in the water, itself in part a function of the dilution of the sewage, either of two possible causes of decomposition may be taken. Under stagnant, anaerobic conditions the rate of decomposition is slower and the products remain objectionable on both sanitary and aesthetic grounds. Under the aerobic conditions that generally obtain where the dilution is satisfactory, the rate is higher and the products are harmless.

The decomposition is accomplished mainly by the action of micro-organisms, and under aerobic conditions, is promoted by factors favoring the growth and activity of the micro-organisms Temperature is particularly important, the rate of decomposition being materially higher in the warm waters characteristic of Hawaii than in the cold waters of or flowing from high latitudes. The particle size is important because with fineness of particles goes a high ratio of surface to volume. Hydrogen ion and other chemical concentrations may be influential.

The most important effect of decomposition is, of course, the reduction in concentration of pathogenic micro-organisms, notably bacteria. This is not ordinarily measured directly, but by concentration of certain index coliforms, streptococci, etc. Local studies (Iha, 1960) have shown that bacterial action of the sea water predominates over the effects of bacteriophages, protozoans, sedimentation, or solar radiation in reducing numbers of sewage bacteria.

8.2 Estimation of Rates of Transport, Dispersal, and Bacterial Die-off

Although the various processes in bacterial transport, dispersal, and die-off in the sewage overlap and influence each other, their effects cannot be estimated unless they are assumed to be somewhat separable. Conventionally, two to five separate calculations have been involved treating two separate stages as follows:

1. Initial stage: Estimation of initial dilution and dimensions of initial field.
2. Final stage: Calculation of combined effects of eddy diffusion, advection and bacterial die-off in a steady current; calculation of effects of eddy diffusion and bacterial die-off and superposition of effects of steady or slowly varying currents; or calculation of either of the above without the bacterial die-off and superposition of the effects of bacterial die-off.

For the calculation of the effects in the jet or cone from a diffuser several formulas are available, some rational and some empirical (for a summary see Hyperion Engineers, 1957), the most complete of which is one by Rawn, Bowerman, and Brooks (1959). The results vary somewhat, and there is some uncertainty as to their correspondence to the initial parameters required in the eddy diffusion calculation. Most significantly perhaps, the effects of the radial spread of the sewage due to its head at the surface appear never to have been included in an analysis.

The great diversity of methods of estimation occurs in the calculation of diffusion effects. The basic reasons for the diversity are the following:

1. Eddy diffusion is so extremely complicated a phenomenon that there is as yet no complete agreement even as to basic conceptions of its mechanism.
2. (a) The eddy diffusivity is not a constant in a particular fluid, as is its molecular diffusivity, but varies with the scale of the phenomenon being studied. (b) The relationship between diffusivity and scale may be quite complex. (c) Even for simple cases there is disagreement as to the scale law appropriate for adoption.
3. The differential equations, at best, are so complex that, in order to permit their solution, assumptions and approximations must be made that render questionable the extent to which the solutions are valid.

Good summaries of diffusion concepts and scale laws are given by Schoenfeld and Groen (1961) and Okubo (1962), a simple method of analysis is given by Brooks (1960), and a practical evaluation of several formulas, rational and empirical, is given by Hyperion Engineers (1957).

Bacterial die-off is usually assumed to be exponential with time, although other, generally more complicated, relationships have been proposed (see Hyperion Engineers, 1957). However, the appropriate exponential constant obviously must vary considerably, depending on the availability of oxygen in the water, the temperature of the water, the particle size distribution in the sewage, and other chemical and physical characteristics of the sewage.

The current data, by itself or in combination with calculated diffusion effects, may be used in the following ways:

1. The estimation of the range of likely transport directions and velocities from prospective sewage release points. The distances to which the directions of transport and the velocities are of interest depend, of course, on the rates of dilution and bacterial die-off and the lengths to which the sewage may travel before the bacterial concentrations drop to insignificance.
2. Appraisal of the likelihood of reinjection of sewage into a dispersing sewage field due to current reversal.
3. Estimation of the general magnitude of dilution as a function of distance and direction from prospective sewage release points, using Lagrangian types of approach, such as those of Joseph and Sendner (1958) and Hela and Voipio (1960) from the center of a patch of sewage introduced essentially instantaneously into the current and integrating numerically to determine the effects of continuous introduction and advection.
4. Estimation of the efficiency of general flushing of bays and similar coastal areas, using the strengths of current in and out of the bays by the method discussed by Schoenfeld and

Groen (1961).

5. The selection of points probably favorable for sewage release, i.e., points from which transport to shorelines of concern is very slow or infrequent.

6. Appraisal of the possibility of accumulation of sewage in current convergences.

8.3 Requirements in Coastal Current Studies for Sewage Disposal Projects

Certain complications seem liable in Hawaii to render inadequate for actual design purposes the accuracy of predictions of sewage dispersal based solely on assumed currents and either rational or empirical formulas for diffusion. Among these may be mentioned:

1. The effects of the similarities in size between the sewage clouds of interest and both tidal ellipses and coastal and bottom irregularities, which restrict the approximation of eddy and tidal effects by either pure eddy diffusion of simple scale law or pure advection.

2. The complications of wind-driven currents at variance with deeper currents.

3. The significant increase in thickness of the sewage fields as the sewage is diluted.

The inescapable conclusion, then, is that a thorough local investigation must be made at the site of any major sewer outfall of uncertain effects, or at any major planned sewer outfall. Such an investigation would involve the following stages:

1. Establishment of at least one and for a complicated area

preferably two or more current-meter stations for long-term (1 year or more) continuous operation in the area, at points to be determined on the basis of the current components and pattern anticipated.

2. Conduction of drogue, dye, and supplementary short-term current meter studies throughout the area, at intervals and over periods, to outline tidal and climatic effects, correlating these with wind, waves, tide, and tidal currents.
3. Determination from general considerations, from the results of monitoring, and from estimates of dilution and estimates of bacterial die-off, the critical conditions in the area.
4. At times representative of critical conditions determine dilution over the field by release of dye or other traces in sufficient quantities, and preferably by continuous introduction, at outfall sites or prospective outfall sites.

Studies of the sort outlined, to be adequate for design purposes, will be far more extensive and costly than the studies that have customarily been made in the past in Hawaii in connection with sewer outfall projects. They will be justified, however, by the gains from economies in sewage treatment and outfall construction that they will make possible, and by the avoidance of losses that may be incurred through restriction of shoreline uses due to health hazards if sewer outfall plans prove inadequate.

9. CONCLUSIONS AND RECOMMENDATIONS

Various wastes are discharged at sea in Hawaii. Problems arise from several, especially from sewage. The following major conclusions and recommendations regarding the coastal currents of the Islands and their effects on the dispersal of sewage at sea may be listed:

1. The dispersal of the sewage in the sea is critically determined by coastal currents in the vicinity of outfalls.

2. The coastal current may have several significant components: the permanent flow, tidal currents, wind-driven currents, and mass transport. At most places the tidal components predominate.

3. The tide waves move through the archipelago from north-northeast to south-southwest. As a result of the superposition of the generally west-northwest setting permanent flow, the flood currents diverge somewhere off the northeast side of each island, swing clockwise around the southeastern shore and counterclockwise around the southwestern shore, and converge off the southwest side. The ebb currents diverge somewhere on the south side of the island, swing clockwise around the western shore and counterclockwise around the eastern shore, and converge on the north side. Along certain north-northeastern shores the current may set almost constantly west-northwesterly, and along certain south-southeastern shores there may be almost constantly a reverse set.

4. The tidal current movements tend to be reciprocating near shore and elliptical offshore. Convergences and divergences result over the slopes of the islands.

5. Irregularities in the shoreline and bottom configuration, together with inertial effects, cause considerable phase disturbances, distortion, and eddies in the current patterns.

6. Over reefs and in lagoons the major currents are generally initiated by mass transport associated with waves.

7. The wind tends to drive the surface water in the direction of the wind's travel, which may be onshore or offshore although the currents in depth set predominantly alongshore. Wind effects predominate in the control of surface currents in protected bays.

8. Except in the wind-driven surface currents, seasonal changes appear to be of minor significance.

9. With the outflow of fresh sewage into salt water, an independent circulation is induced in the vicinity of the outfall.

10. Turbidity, bacterial concentrations, and dye have proved useable as tracers fcr sewage.

11. The critical conditions with regard to sewage disposal are likely to result from a combination of onshore wind-driven current and some particular tidal current direction.

12. There may be a very few sites at which an offshore set of the current is so predominant that untreated sewage may safely be introduced through outfalls of normal length. In general, however, alongshore and shoreward sets occur, especially in the surface layers due to wind action, with sufficient frequency as to make inadvisable large discharges of untreated sewage within a few miles in any direction from a shoreline intensively used for recreation or for fishing.

13. The critical conditions for the Sand Island sewer on Oahu are an ebb current, perhaps prolonged by an eddy, and a kona wind. Even during trade-wind conditions, sewage-laden water has been traced east as far as the Kewalo entrance in about 6 hours. It must flow farther east on occasion, and the floatables, in particular, may be driven onshore. On other occasions the sewage-laden water drifts north or west.

14. The bottom deposits off Sand Island sewer do not indicate any accumulation or excessive pollution at the bottom.

15. Current velocities and mixing in depth are sufficient on open coasts generally to minimize the risk of stagnation.

16. In deep estuaries, protected bays, and harbors, however, there may be stagnant conditions. Such conditions have been noted in parts of Kaneohe Bay and in Hilo Harbor.

17. The complexities of the coastal current patterns and the status of theoretical knowledge of the eddy diffusivity associated with them are such that no calculations of sewage dispersal from general principles and assumed conditions are likely to be entirely satisfactory.

18. Intensive local investigation should be made of dispersal from major existing outfalls and planned outfalls, involving continuous monitoring by current meter at a few sites, drogue and dye studies to outline current patterns, and dye dilution studies to indicate dilution at critical periods.

10. ANNOTATED BIBLIOGRAPHY OF COASTAL CURRENTS IN HAWAII

Austin, H.A.R. & Associates. 1961.

Investigation, studies, and preliminary plans with recommendations for a sewerage system within the Kailua-Kona area, Kona, Hawaii. Report to Hawaii County.

Contamination in Kailua Bay now stems from cesspools near shore. Central sewer system with complete treatment and inland discharge is recommended because floatables from any ocean outfall would be driven onshore by winds. Currents are not discussed, but measurements by Department of Health, shown in exhibits, indicate current setting usually northwest along shore sometimes having onshore or offshore components, and sometimes reversing southeast.

Austin, H.A.R. & Associates and Law & Wilson. 1960.

Engineering feasibility studies: Part I of the comprehensive plan, Ala Moana Reef. Report to Hawaii Deparment of Land and Natural Resources.

Current measurements made off Ala Moana reef and in channels November 1959 to March 1960 by 10-ft. float. Current generally set outward through Kewalo and Ala Moana channels, but may briefly set inward on a rising tide. Illustration shows currents off reef setting generally to northwest though sometimes in reverse direction. Most measurements were made at high or falling tide.

Austin, Smith, & Associates. 1960.

Engineering investigation report for improvement to Pearl Harbor sewerage system, Pearl Harbor, Oahu, Hawaii. Report to U. S. Navy Dist. Public Works Office, 14th Naval District.

Current studies made in and outside Pearl Harbor entrance by surface and subsurface floats. Surface floats indicated current sets resulting from wind, away from shore in trade weather, toward shore in Kona. Subsurface floats indicated reversing current off Hickam AFB and in Pearl Harbor entrance, but with a southwestward set superimposed at the entrance which dominates at slack water.

Austin, Smith, & Associates. 1961.

Engineering investigation for the proposed Pearl City Sewage treatment plant, Ewa, Oahu, Hawaii. Report to Division of Sewers, City and County of Honolulu.

Tides in Middle Loch found to correspond in place with those in ocean, though water level higher owing to fresh water discharge. Current studies indicate that floating material discharged from proposed outfall in Middle Loch will be deposited on Middle Loch beaches, depending on wind. Stream flows and tides are also influential. Studies are continuing.

Austin, Smith, & Associates. 1961.

North Honolulu sewerage studies. Report to Division of Sewers, City and County of Honolulu.

Describes performance of Sand Island sewer outfall, constructed in 1950. Illustrations show slick fields from outfall in tradewind and kona conditions. Time, tide, and detailed wind conditions are not given.

Austin, Smith, & Associates and Metcalf & Eddy. 1962.

Report and master plan of the Pearl City Sewage Treatment Plant near Pearl City, Oahu, Hawaii. Report to Department of Public Works, City and County of Honolulu.

Results of bacteriological surveys show generally progressively increasing coliform indices throughout harbor. No new current surveys reported, but results of Austin, Smith, & Associates 1962 surveys used to estimate 8- and 24-hr. "influence areas" about proposed sewer outlet in middle Loch for various tide and wind conditions. Treatment in successively greater degrees is proposed.

Belt, Collins, & Associates. 1961.

Hilo sewer system study. Vol. I. Hilo Bay area pollution and preliminary investigation on its abatement and other related studies. Report to Department of Public Works, County of Hawaii.

Study of physical, chemical, and bacteriological conditions in Hilo Bay in 1960 showed effects of pollution and stagnation. Salinity was low, turbidity high, pH generally on acid side, DO low, BOD high, nitrates and phosphates high. Pollution sources were principally Waiakea Mill, Flintcote wallboard plant, and sewer outfall. Water in bay is bacteriologically in prohibited class for bathing 33% of time, completely satisfactory only 16% of time. Muddy water patches from sugar mills from Hakalau south show southward drift, at Laupahoehoe sometimes southward sometimes northward. Current observations in western part of bay in April 1960 and January 1961 by dye, surface, and subsurface floats show reversing movements with outward trend resulting from discharge of Wailuku River. Wind effects were negligible. Tidal effects were not described but seem very important from charts provided.

Belt, Collins, & Associates. 1962.

Kaiaka Bay small boat harbor: Preliminary engineering and feasibility study.

Currents were observed on 2 mornings in the winter of 1961 by dye and various sorts of surface floats. On both days surface drift in Kaiaka Bay paralleled the wind, setting northwest on one morning, west on the other. Direct wind effect on the floats was not taken into account. Outside the bay the current set was southwesterly on one morning. Bacterial counts in the bay were high inside the bay, low outside, the oxygen content is low in the bay, indicating stagnation.

Belt, Collins, & Associates. 1962.

Kaneilio Point small boat harbor, Waianae, Oahu: Preliminary engineering and feasibility study. Report to Harbors Division, Hawaii Department of Transportation.

Off Kaneilio point currents, investigated by dye and floats, set consistently northerly during one day's observation (on flood tide) in stormy kona weather, northerly in the morning (ebb tide) and southerly in the afternoon (after tide turn) in one day in trade weather. Bacterial analyses showed excessive pollution near the sewage outfall but generally satisfactory to doubtful levels elsewhere along the shoreline.

Belt, Collins, & Associates. 1962.

Waialua Bay pollution study, Haleiwa, Oahu, Hawaii. Report to Harbors Division, Hawaii Department of Transportation.

Currents studied by surface and subsurface floats, dye, and drift cards. Bacteriological analysis run on samples. In trade weather on rising tide and just after high tide, current from bay sets southwest. When streams were in flood, kona wind currents were to NW just after low tide, moving to N on falling tide. During light westerlies and with heavy surf currents set toward WNW on rising tide, NNW just after high tide. Coliform counts were high at Haleiwa Beach during trade wind conditions, high generally during flood and high surf conditions.

Bureau of Sanitation. 1941.

Honolulu sewage disposal survey, May 1940 - September 1941.

Report to Honolulu Chamber of Commerce and Territory Board of Health.

Refers to float surveys of currents made in vicinity of Kewalo outfall, 1926, described as inadequate. Currents are difficult to determine but seem to flow either in Diamond Head or Ewa direction. Slicks are noted frequently on calm days to extend toward Waikiki, once to about 5000 feet, with small organic particles going beyond. Thorough bacterial analyses showed pollution field southeast of outfall over 17 months. Practically all monthly sample fields showed a tongue of high pollution extending southwestward from outfalls; the greatest extent being in February 1941, when there was a B.coli concentration $>1000/100$ ml 1 mile off Kuhio Beach and $>100/100$ ml $\frac{1}{4}$ mile off the natatorium. The Ala Wai canal served as an additional center of pollution.

Coast and Geodetic Survey. 1963.

U. S. Coast Pilot 7: Pacific Coast 9th edition.

There is a prevailing westerly drift in the vicinity of the Hawaiian Islands. Variability is believed mostly a function of wind, but strong northeast currents setting against trades have been reported. The currents in the Alenuihaha Channel and around Kauai are reported to be controlled especially by the wind. Around each island currents have been reported to set generally to west or northwest, however, counter currents have been reported close inshore in some areas, as around the southern part of Hawaii. Rips have been noted near Keahole Point on Hawaii, Laau Point on Molokai, Kaena Point and Kahuku Point on Oahu. Recent observations, mostly in 1962, indicate that the currents reverse with tides in many places, even at some places where previous information suggested a non-reversing current. Tidal currents were noted specifically near Mahukona on Hawaii; Hana, Cape Hanamanioa, Lahaina, and Kekaa Point on Maui; in the Kalohi Channel; Maunalua Bay and Honolulu on Oahu; Mana and Nohili on Kauai; Kamalino on Niihau, and in the Lehua Channel.

Coast and Geodetic Survey. 1963.

Tidal Current Tables, 1963, Pacific Coast of North America and Asia.

The following tidal currents are listed in Hawaiian waters:

Place	Lat.	Long.	Max. flood		Max. ebb	
			Dir.	Vel.	Dir.	Vel.
Kalohi Channel	21°02'	156°56'	235°	0.4 kt	70°	0.5 kt
Auau Channel	20°53'	156°43'	70°	0.6 kt	270°	0.5 kt

Division of Sewers. 1951.

Report on ocean current studies for Sand Island outfall sewer,

Honolulu, Oahu, T. H.

Drogue and current pole measurements were conducted 2 or 3 times a week in various periods of weather September 1950 to May 1951 from near the end of the Sand Island outfall. Current pole measurements indicated currents setting on the average 30° to the right of the wind and averaging about 4% of wind velocity with better correlation when winds were strong than otherwise. A "tide" current was mentioned but apparently in the sense of a prevailing flow. Possibility of reversing tidal currents was not recognized. Current reversals were noted but ascribed to eddies or to tidal outflow from Pearl Harbor. Current at the outfall was estimated to set W, 270 days, E, 37 days, S, 44 days and N, 14 days out of the year. Report does not include nor illustrate data except for 16-17 May 1951.

Division of Sewers. 1957.

A report on sewerage master plan for Kaneohe, Koolaupoko, Oahu.

Report to Department of Public Works, City and County of Honolulu.

Bacterial analyses in Kaneohe Bay show very low concentrations except close to shore. No current studies were made and wind and tide conditions at times of sampling are not given.

Division of Sewers. 1957.

A report on sewerage master plan for Waipahu, Ewa, Oahu.

Report to Department of Public Works, City and County of Honolulu.

Recommends outfalls for treated sewage in shallow water in West Loch in belief oxygen will be adequate for aerobic decomposition, and slick field will not be objectionable. Need for control of hydrograph at outfall recognized to prevent anaerobic bottom deposits. No current measurements.

Division of Sewers. 1958.

Report on sewerage master plan for Aiea to Pearl City, Ewa, Oahu.

Report to Department of Public Works, City and County of Honolulu.

Present Aiea sewer outfall in East Loch, Pearl Harbor at base Pearl City Peninsula. Waiawa Stream discharge counted on for dispersal from proposed outfall for sewage in Middle Loch, but current studies recommended.

Helfrich, P., and Kohn, A. J. 1955.

A survey to estimate the major biological effect of a dredging operation by the Lihue Plantation Company on North Kapaa Reef, Kapaa, Kauai. Report to Lihue Plantation Company.

Float measurements in October and November 1955 in a variety of wave and wind conditions showed southerly currents on the North Kapaa reef resulting from mass transport by breakers onto the reef. Average values of current were about 1 ft/sec on the central portion of the reef and about 1.5 ft/sec at the south edge near an inlet.

Herschler & Randolph. 1962.

Study of pollution in Kahului Bay, Maui, Hawaii.

Report to Hawaii State Department of Health.

Sewage is discharged to bay through Kahului outfall east of Kahului Harbor and Wailuku outfall west of harbor. Additional pollution reaches bay through Iao and Kalialinui Streams. Currents were measured with surface and subsurface drogues, lath floats, drift bottles, drift cards, and dye. All measurements were made during the day during trade wind weather. Drogues, especially, were observed to be affected directly by the wind and almost all apparent sets, both inside and outside harbor, were toward west or southwest parallel to the wind. Dye studies showed tidal currents reversing near harbor mouth and a possible eddy near Wailuku outfall, but otherwise westward drift outside harbor, turning to northwest off Iao Stream mouth; but no tidal reversal. Upwelling was noted outside the east breakwater on a rising tide. Chemical sampling showed generally high DO and low BOD except in the vicinity of the Kahului outfall. Chlorides were in general low at the surface at the southwest shore of the harbor and increased toward the harbor mouth and in depth. Bacteriological sampling showed a high coliform field at the surface outside the breakwaters, but low concentration generally at the surface elsewhere. Illustrations show that in the harbor coliform the concentrations were consistently greater at depth than at the surface. In the vicinity of the Wailuku outfall the pollution field seems from an illustration to drift southeastward at low tide and northward at high tide. A new Kahului outfall to deeper water is recommended.

Holmes & Narver, Inc. 1957.

Report and master plan of sewerage facility for Kailua, Koolaupoko,

Oahu. Report to City and County of Honolulu.

Currents outside reefs in Kailua Bay are reported to parallel shore, though direction is not indicated. The currents inside the reefs are reported to be only wind-generated and weak. Oxygen concentrations are high. No details of times or conditions of observation are given. A sewage treatment plant on Mokapu peninsula, a temporary outfall to Nuupia Pond, and an eventual outfall to Kailua Bay are recommended.

Holmes & Narver and Belt, Collins, & Associates. 1959.

Kailua ocean outfall sewer, ocean portion. Kailua sewage treatment plant, Kailua, Koolaupoko, Oahu, Hawaii. Report to Department of Public Works, City and County of Honolulu.

Report on oceanographic environment of proposed Kailua sewer outfall at base of Mokapu peninsula based on 12-months observations. Current observations made with dye, surface floats, and subsurface drogues. Wind conditions and tide during period of observations illustrated, but not in such a way that changes can be correlated with current changes. Conclusions are drawn that surface currents are wind driven, sometimes slower, sometimes faster than Eckman's theory indicates, but usually trending to the right of the downwind direction, in accordance with theory. Subsurface currents, however, move generally to the north and never to the south, in spite of winds generally from the north. Tide effects are not discussed and are not apparent in charts. Kailua Bay is now unpolluted except at the outlet of the Kawainui Canal. Chemistry is normal except for lower salinity, higher nitrogen, and lower oxygen near the canal outlet. Dilution and bacterial die-off at the proposed sewer outlet were checked with injected mixtures of dye, radioactive carbonate, and sewage. Dilution generally reduced chemical concentrations within 90 minutes to 0.1 to 0.3 of concentration 5 minutes after injection. Bacterial die-off in the same time reduced concentrations to 1/1000 to 1/100, even allowing for dilution. The outfall site is judged satisfactory.

Holmes & Narver and Belt, Collins, & Associates. 1959.

Nuupia Pond outfall study. Kailua sewage treatment plant, Kailua, Koolaupoko, Oahu. Report to Department of Public Works, City and County of Honolulu.

Investigation of Nuupia Pond (shallow walled-off arm of Kaneohe Bay) as a potential temporary outfall site for the Kailua sewer system. Currents in the pond were found to be wind driven. Aeration and mixing are sufficient to allow treated sewage to be discharged into the pond as an interim measure.

Hyperion Engineers. 1957.

Ocean outfall design.

Brooks T (coefficient of time required for 90% bacterial die-off) and Conways K (log dilution ratio/distance) are estimated from 1952 survey of pollution from Ala Moana and Ward Avenue outfalls

and estimated or assumed values. Assumptions are: initial dilutions of 8 for Ala Moana, 20 for Ward Avenue; initial concentration of 430,000 coliforms/ml in the boils, field depth 3 to 4 ft and width 1000 ft, westward current of 0.7 ft/sec, initial eddy diffusivity of 3.68 $ft^{2/3}$ hr^{-1}. T ranged from 0.21 hr at 1700 ft to 11.05 hr at 12,000 ft; K from 21 x 10^{-4}/ft at 1700 ft to 4.7 x 10^{-4}/ft at 12,000 ft. The values of T are particularly low and those of K particularly high as compared with East and West Coast experience. The increase in T and decrease in K with distance are generally found, although there are supposed to be constants.

Iha, T. H. 1960.

Survival of sewage bacteria in the sea.

M.S. Thesis, University of Hawaii.

Review of previous work shows bacterial concentrations in polluted sea water always lower than explicable by dilution alone. Bacterial disappearance attributed variously to bactericidal agents in sea water, bacteriophages, protozoans, adsorption and sedimentation, solar radiation. Various bacteria found differentially resistant. Previous work all either done in laboratory or with dialysis tubes and laboratory cultures in sea. Present experiment introduced radioactive sewage in Kailua Bay. Dilution measured by decrease in radioactivity. Concentrations of both coliforms and enterococci, corrected for dilution, showed reduction of 99.99 percent in 30 minutes. Sedimentation was insignificant and bactericidal action judged predominant. Enterococci survival was higher than coliform. Laboratory studies confirmed insignificance of sedimentation. Longer bacterial survival in laboratory considered due to higher ratio of solid surfaces to volume in laboratory. Effects of temperature variation were found insignificant. Storage of samples might account for 10% at most of bacterial reduction in dilute samples.

Industrial Waste Disposal Study Commission. 1955.

Report of Industrial Waste Disposal Study Commission to 28th

Legislature, Territory of Hawaii.

Tabulation of industrial waste disposals and reports from concerns and agencies disposing of wastes or interested in results. Board of Agriculture and Forestry and Tuna Boat Owner's Assn. reported frequent oxygen deficiency in Honolulu and pollution in West Loch, Pearl Harbor on Oahu. Damage to inshore fisheries on Kauai, reduction in bait fish production in Hilo Harbor and interference with shore recreation and fishing along Hamakua Coast on Hawaii, interference with shore recreation near Iao Stream mouth on Maui.

Department of Health reported odor problems in Hilo Bay, reduction in problems on Maui. American Factors reported that at the outfall for muddy water from Lihue Mill on Kauai current sets usually to south, though sometimes to the north in kona weather.

Keller, A. R., S. W. Tay, & G. M. Collins. 1920.

Preliminary report on proposed sewer extensions in the Waikiki and Kalihi Districts; also alleviation of the nuisance of Nuuanu Stream. Report to Mayor and Board of Supervisors, City and County of Honolulu.

Tidal and stream-flow flushing is insufficient to overcome pollution and stagnation caused by overflows from the sanitary sewer. Though no current measurements appear to have been made at Waikiki tidal currents are reported such that sewage discharged offshore might be carried inshore. No outfall closer to Waikiki than that at Kakaako is recommended. Float observations in Kalihi channel indicate that prevailing current will carry sewage seaward from a proposed new outfall at Kalihi. Ultimately this sewage, that from the old Kalihi outfall and from Fort Shafter, will have to be connected to a central pumping plant discharging over the reef.

Lublin, McGaughey, & Associates. 1962.

Plan of development for Hana Harbor. Report to Hawaii State Department of Transportation.

Tidal currents are reported of relatively low velocity in Hana Harbor except in vicinity of existing wharf and Puukii Island. Direction of current not given. No details as to time of observation nor conditions pertaining at time.

Lublin, McGauhey, & Associates. 1962.

Plan of development for sampan harbor, Wailoa River, Hilo, Hawaii. Report to Hawaii Department of Transportation.

Wailoa River peak discharge of 1000 ft^3/sec (1.3 ft/sec) can be expected annually. Maximum tidal current 1.0 ft/sec on spring ebb.

Marine Advisers, Inc. 1961-1962.

Oceanographic investigation in connection with proposed Waimanalo outfall. Report made to R.M. Towill Corporation-Engineers.

Set of charts of the Waimanalo Bay area of data taken on 16 different days between September 25, 1961 and October 31, 1962. Fifteen charts show drogue tracks vs tides and wind conditions on as many days; nine charts show temperature and salinity; and nine charts show dissolved oxygen concentration and water density for as many days. Three charts show bacterial analysis on four different days: standard plate count, coliform count, and enterococci count. Three charts show nitrates and phosphates and three charts show biochemical oxygen demands and pH for as many days. One chart shows suspended solids on one day.

Currents were found to reverse, but do not follow any simple pattern. On two days drogues released in the bay drifted around Makapuu Point and were picked up off Hanauma Bay. On one of these days there was a slight kona wind, and on the other day there was no wind. In general the surface drogues showed a definite tendency to go down wind, with the deep drogues (depth not known) showing a tendency to follow the depth contours. [Report text not seen.]

Metcalf & Eddy. 1944.

Report to Honolulu Sewerage Committee upon sewerage and sewerage disposal, vols. I and II. Boston.

Comprehensive report on Honolulu sewerage problems. Discusses history of sewer system and outfalls. Reports observations April-June 1944 on slick field, sewage solids, and bacteria from Kewalo sewer outfalls; also Tay's observations in December 1940-January 1941 (Bureau of Sanitation, 1941). Concludes that under trade-wind conditions sewage moves entirely toward west from Kewalo, though easterly movement was found by Tay in winter. No details of times and tide conditions at times of observation, except for two days in July 1944 when milk bottle caps traced from Kewalo outlet, moving west on one day and north and west on second, with wind from south. Concludes that sewage should be led to Sand Island, and subjected there to short-period sedimentation.

Public Health Service. 1963.

Municipal and industrial waste facilities, 1962 inventory, Hawaii. U. S. Department of Health, Education, and Welfare.

Tabulation of municipal and industrial waste facilities for all of

the islands, with notes on type of waste, treatment, etc. and reference to health problems resulting. No information on currents.

Sunn, Low, Tom, & Hara. 1962.

Report on oceanographic survey and study to sewage disposal for Waianae, Oahu. Report to Department Public Works, City and County of Honolulu.

Bacteriological analyses showed Waianae beaches to be generally Class A except in vicinity existing Kaneilio Point outfall. High coliform counts were found more than 1000 feet from this outfall. Dissolved oxygen was generally high except near outfall and in a sometimes-isolated stream mouth. BOD phosphates and nitrates were generally low. Salinity was generally reduced from normal but salinity profiles were inconsistent. Transparency was exceptionally high. The depth to the thermocline was about 300 feet in winter, 150 feet in summer. Current studies extended a year and included two 24-hr studies. Drift cards, drift bottles, drogues and dye were used. Current-meter studies were unsuccessful. Currents were correlated with tides as locally recorded. Some drift cards and drift bottles released off Waianae beaches were found on shores to southeast within several tenths of a mile in a few hours, and as far as Ewa Beach in 8 days, and Keehi Lagoon in 27 days. Others were found on shores to the northwest within several tenths of a mile in a few hours, as far as Kaena Point in 7 days, and on Kauai and Niihau in 10 to 23 days. Drogue studies indicated currents induced largely by tides, with movements preponderantly oscillatory parallel to shore. Off points, flood current sets southeast, ebb current northwest. Eddies are set up by irregular bottom topography, as at Pokai Bay. Generalized flood and ebb patterns were portrayed. Trade winds tended to deflect drogues seaward; kona winds landward. Preliminary dilution was calculated by Rawn-Palmer formula and subsequent dilution and die-off by Pomeroy formula for proposed outfalls. Primary sewage treatment with a 2400-foot outfall was recommended.

Sunn, Low, Tom, & Hara. 1962.

Report on sewage disposal for the Hawaii-Kai development.

[Report text not seen.] Illustrations of results of three cruises show semi-diurnal tidal currents measured by drogues, setting northeast with ebb (velocities to 89 ft/min), southwest with flood (velocities to 107 ft/min). Change from flood to ebb. Drift cards and bottles released in area were picked up at Hanauma Bay (2 days min.), Makapuu Beach (2 days), Kailua Beach (2 days), Kaneohe Bay (2 days), Maunalua Bay (14 days), Black Point (5 days), Honolulu Harbor (16 days), Wailua, Kauai (23 days).

Tippets, Abbett, McCarthy, & Stratton. 1961.

Development plan, deepwater port at Barbers Point, Oahu, Hawaii.

Report to Estate of James Campbell.

Tidal currents are reported generally weak. A westward drift is said to prevail. Current measurements at Brown's Camp indicate variability in direction and velocity range from 0 to 0.5 kts, occasionally to 2 kts.

11. REFERENCES

Anonymous. 1963. Oceanic eddies southwest of Oahu surveyed. National Oceanographic Data Center Newsletter 8-63: 6-7.

Austin, H. A. R. & Associates, Ltd. 1961. Report to the County of Hawaii covering the investigation, studies, and preliminary plans with recommendations for a sewerage system within the Kailua-Kona Area, Kona, Hawaii. 27 pp.

Austin, H. A. R. & Associates and Law & Wilson. 1960. Engineering feasibility studies: Part I of the comprehensive plan, Ala Moana Reef. Report to Hawaii Department of Land and Natural Resources. 83 pp.

Austin, Smith, & Associates, Inc. 1960. Engineering investigation report for improvement to Pearl Harbor sewerage system, Pearl Harbor, Hawaii. Rept. to U. S. Navy Dist. Public Works Office, 14th Naval Dist.

Austin, Smith, & Associate, Inc. 1961a. Engineering investigation for the proposed Pearl City Sewage treatment plant, Ewa, Oahu, Hawaii. Report to Division of Sewers, City and County of Honolulu.

Austin, Smith, & Associates, Inc. 1961b. North Honolulu Sewerage Studies, November, 1961. Prepared for the Division of Sewers, City and County of Honolulu. 99 pp.

Austin, Smith, & Associates, Inc. 1961c. Report [to Division of Sewers, Department of Public Works, City and County of Honolulu] covering research, topographic and hydrographic surveys, current studies and utility investigations in connection with the preparation of the master plan and report for the proposed Pearl City sewage treatment plant, Ewa, Oahu, Hawaii. About 20 pp.

Austin, Smith, & Associates and Metcalf & Eddy. 1962. Report and master plan of the Pearl City Sewage Treatment Plant near Pearl City, Hawaii. Report to Department of Public Works, City and County of Honolulu.

Avery, Don E., Doak C. Cox, and Taivo Laevastu. 1963. Currents around the Hawaiian Islands. H.I.G. Report No. 26. 40 pp.

Barkley, R. A. (Unpub. ms.) Oceanographic studies in the Central Pacific.

Belt, Collins, & Associates, Ltd. 1961a. Hilo sewer system study. Prepared for Department of Public Works. 94 pp.

Belt, Collins, & Associates, Ltd. 1961b. South Honolulu sewerage study. Prepared for the City and County of Honolulu. 250 pp.

Belt, Collins, & Associates, Ltd. 1962a. Kaiaka Bay small boat harbor preliminary engineering and feasibility study. Prepared for Harbors Division, Depatment of Transportation. 33 pp.

Belt, Collins, & Associates, Ltd. 1962b. Kaneilio Point small boat harbor; preliminary engineering and feasibility study. Prepared for Harbors Division, Department of Transportation. 33 pp.

Belt, Collins, & Associates, Ltd. 1962c. Waialua Bay pollution study, Haleiwa, Oahu. Report to Harbors Division, Department of Transportation.

Brooks, N. H. 1960. Diffusion of sewage effluent in an ocean current. In Pearson, E. H., ed., Proc. ist Intl. Conf. on Waste Disposal in the Marine Environment. Pergamon. p. 246-267.

Brown, R. P. (Ms.) Atlas of surface drift charts for the central North Pacific Ocean (10° to 30°N, 150° to 180°W).

Bureau of Sanitation. 1941. Honolulu sewage disposal survey, May 1940-September 1941. Report to Honolulu Chamber of Commerce and Terr. Hawaii Board of Health.

Chick, Harriet. 1908. Investigation of the laws of disinfection. Hygiene 8: 655.

Coast and Geodetic Survey. 1962. Tide Tables. West Coast North and South America including the Hawaiian Islands. 224 pp.

Coast and Geodetic Survey. 1963a. U. S. Coast Pilot 7: Pacific Coast 9th ed.

Coast and Geodetic Survey. 1963b. Tidal Current Tables, 1963, Pacific Coast of North America and Asia.

Division of Sewers. 1951. Report on ocean current studies for Sand Island outfall sewer, Honolulu, Oahu, T.H. 11 pp. (Mimeo)

Division of Sewers, 1957a. A report on sewerage master plan for Kaneohe, Koolaupoko, Oahu. Department of Public Works, City and County of Honolulu.

Division of Sewers. 1957b. A report on sewerage master plan for Waipahu, Ewa, Oahu. Department of Public Works, City and County of Honolulu. 33 pp.

Division of Sewers. 1958. A report on sewerage master plan for Aiea to Pearl City, Ewa, Oahu. Department of Public Works, City and County of Honolulu. 33 pp.

Fleming, R. H., and D. Heggarty. 1962. Recovery of drift bottles released in the southeastern Chukchi Sea and northern Bering Sea. Univ.

Washington, Department Oceanography, Tech. Rept. No. 70.

Hela, I., and A. Voipio. 1960. Tracer dyes as means of studying turbulent diffusion in the sea. Ann. Acad. Sci. Finnica A (6) 69: 1-9.

Helfrich, P., and A. J. Kohn. 1955. A survey to estimate the major biological effects of a dredging operation by the Lihue Plantation Co. Ltd., on north Kapaa Reef, Kapaa, Kauai. (Ms. report.)

Herschler & Randolph. 1962. Study of pollution in Kahului Bay, Maui, Hawaii. Report to the Department of Health, State of Hawaii. 115 pp.

Holmes & Narver, Inc. 1957. Report and master plan of sewerage facility for Kailua, Koolaupoko, Oahu. Report to City and County of Honolulu.

Holmes & Narver, Inc. and Belt, Collins, & Associates, Ltd. 1959a. Kailua ocean outfall sewer, ocean portion. Kailua sewage treatment plant Kailua, Koolaupoko, Oahu, Hawaii. Report to Department of Public Works, City and County of Honolulu. 125 pp.

Holmes & Narver, Inc. and Belt, Collins, & Associates, Ltd. 1959b. Nuupia Pond outfall--study Kailua sewage treatment plant Kailua, Koolaupoko, Oahu, T.H. Report to Department of Public Works, City and County of Honolulu. 26 pp.

Hydrographic Office. 1947. Atlas of surface currents, northeastern Pacific Ocean. H.O. Pub. No. 570.

Hydrographic Office. 1950. Atlas of surface currents, northwestern Pacific Ocean. H.O. Pub. No. 569.

Hyperion Engineers (a joint venture). 1957. Ocean outfall design. Final report to City of Los Angeles.

Iha, T. H. 1960. Survival of sewage bacteria in the sea. M.S. Thesis, Univ. of Hawaii.

Inman, D. L., W. R. Gayman, and D. C. Cox. 1963. Littoral sedimentary processes on Kauai, a subtropical high island. Pacific Science 17(1): 106-130.

Joseph, F., and H. Sendner. 1958. Uber die horizontale diffusion in Meere. Dtsch. Hydrogr. Zeitschr. 11(2).

Keller, A. R., S. W. Tay, & G. M. Collins. 1920. Preliminary report on proposed sewer extensions in the Waikiki and Kalihi Districts; also alleviation of the nuisance of Nuuanu Stream. Report to Mayor and Board of Supervisors, City and County of Honolulu.

Ketchum, B. H., C. L. Carey, and M. Briggs. 1949. Preliminary studies on the viability and disposal of bacteria in the sea. Limnology, water supply, and waste disposal. Amer. Adv. Sci.

La Fond, Eugene. 1962. Water motions associated with internal waves. <u>In</u> Proc. National Coastal and Shallow Water Research Conference, 1st, Oct. 1961, Baltimore, Los Angeles, and Tallahassee. P. 530.

Laevastu, T., H. Zeitlin and M. K. Song. (Ms.) Investigation of the biological oxygen demand (BOD) of sea water and oxygen production by phytoplankton under different laboratory conditions.

Marine Advisers, Inc. 1961-1962. Oceanographic investigation in connection with the proposed Waimanalo outfall. Report made to R. W. Towill Corporation--Engineers.

Masch, F. D. 1961. Mixing and dispersive action of wind and waves. Univ.

Calif., Berkeley, Inst. Eng. Res., Tech. Rept. Ser. 138, Issue 6. (Mimeo.)

Metcalf & Eddy. 1944. Sewerage and sewage disposal, volumes I and II, December 31, 1944. Report to Honolulu Sewerage Committee. 227 pp.

Neumann, H. 1960. Uber die bearbeitung von strombeobachtungen von mehr als funfzehn tage dauer. Dtsch. Hydrogr. Zeitschr. 13(5): 209-225.

Okubo, Akira. 1962. A review of theoretical models of turbulent diffusion in the sea. The Johns Hopkins Univ., Chesapeake Bay Institute, Tech. Rept. 30. 105 pp.

Public Health Service. 1963. Municipal and industrial waste facilities; 1962 inventory, Hawaii. U. S. Dept of Health, Education, and Welfare.

Rawn, A. M., F. R. Bowerman, and N. H. Brooks. 1959. Diffusers for disposal of sewage in sea water. Amer. Soc. Civil Engrs., Sanitary Eng. Div. 86 (SA 2): 65-105.

Schønfeld, J. C., and P. Groen. 1961. Mixing and exchange processes. In Radioactive Waste Disposal Into the Sea. Internatl. Atomic Energy Agency, Safety Ser. 5: 100-132.

Sunn, Low, Tom, & Hara, Inc. 1962a. Report on oceanographic survey and study relative to sewage disposal for Waianae, Oahu. Report to City and County of Honolulu. 36 pp.

Sunn, Low, Tom, & Hara, Inc. 1962b. Report on sewage disposal for the Hawaii Kai Development, Hawaii Kai Community Services Company. 25 pp.

Tippets, Abbett, McCarthy, & Stratton. 1961. Development plan, deepwater port at Barber's Point, Oahu, Hawaii. Rept. to Estate of James Campbell.

Tomczak, G. 1962. Recent investigations with drift cards for determining the influence of the wind on surface current. ICES CM 1962 Hydrogr. Comm. No. 66.

Vaccaro, R. F., M. P. Briggs, C. L. Carey, and B. H. Ketchum. 1950. Viability of *Escherichia coli* in sea water. Amer. J. Public Health. 40: 1257-1265.

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